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FURTHER PHYSIOLOGIC RESEARCH ON HUMAN TUMBLING

JOHN G. FLETCHER, Ph. D.

USAF School of Aerospace Medicine
Aerospace Medical Division (AFSC)
Brooks Air Force Base, Texas

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FOREWORD

This report was prepared by Systems Research Laboratories, Inc., San Antonio, Tex., under contract No. AF 41(609)-2897 and task No. 793003. The work was accomplished between January 1967 and May 1968. The paper was submitted for publication on 9 July 1968

W. E Rothe of Systems Research Laboratories was project manager Dr. John G. Fletcher was principal investigator Dr. Samuel T Lim was resident physiologist until 24 November 1967, and Dr J. Lipana was in residence in the period from March through April 1968. Dr. Sidney D. Leverett, Jr, Biodynamics Branch, USAF School of Aerospace Medicine, was monitor.

On-site execution was conducted by E. Pope and R. Williams. W. Bowie was medical technician in charge of on-man instrumentation and records. The USAF Biodynamics Branch team, under J. Jaggars, collaborated in both the engineering and operational phases.

The author expresses thanks to J Piotrowski, Dr. J. Lipana, and W. E. Rothe for their help in the reporting sequence. Special thanks are due to the medical monitors under Major William Brown for their willing collaboration and continuous support. The names of the subject panel are listed in the appendix.

The combination of the employees of Systems Research Laboratories and the staff of the USAF School of Aerospace Medicine formed a very effective working team that developed unique competence in handling the new facility. The team was successful in extending knowledge about the hazards of tumbling and the capability of trained men to withstand the stress involved.

This report has been reviewed and is approved.

GEORGE E. SCHAFER
Colonel, USAF, MC
Commander

ABSTRACT

Twelve tumbling problems, ranging from impaired performance to water immersion deconditioning, were investigated by using an important training and physiologic research tool—the All-Attitude Air-Bearing Research and Training Simulator (ARTS). The ARTS can move up to 60 rpm in roll, pitch, yaw, any combination of these, or random axis rotation.

In 280 test runs on a subject panel of 24 experienced and 5 inexperienced men, it was shown that among healthy persons there is a wide spectrum in their tolerance to tumbling. Evidence was obtained that men may be disoriented by tumbling, yet show no symptoms of motion sickness, and vice versa. In tests of numeric processing capability, random rotation, reliance on auditory input, and slow tumbling at 3 to 6 rpm (or above 30 rpm) gave the most difficulty. Experiments with occlusion of the blood circulation by using thigh cuffs suggested the importance of volume redistribution in controlling heart rate. The characteristic pattern of rhythmic cardio-acceleration and cardio-deceleration due to slow tumbling was abolished in 1 subject at 30 rpm, pitch forward. Combined stresses of tumbling and cold are tolerated better than combined stresses of tumbling and heat.

Other investigations which are described include: complex patterns of rotation and tumbling, respiratory effects, phase shifts at different rpm's, subject capability to perform a simulated flying movement during turning, body position effects, and the ability of some subjects to withstand continuous tumbling for at least 1 hour.

Persons resistant to disorientation and able to perform well under multiple stress may be selected (and perhaps trained) by use of the ARTS and the experimental technic described.

CONTENTS

FURTHER PHYSIOLOGIC RESEARCH ON HUMAN TUMBLING

I. INTRODUCTION

The All-Attitude Air-Bearing Research and Training Simulator (ARTS) is a physiologic test vehicle with numerous applications. Circulatory, temperature, and respiratory studies, performance tests, subject screening and training, and simulation of space tumbling are some of the activities selected for study because of their current importance and interest. Other studies on posture, dynamic body movements, and multiple body stresses have been begun or are anticipated. The ARTS has dramatic potential for totally new investigation of man's performance and capability of being trained for space operations.

In order to understand the structure, function, and performance of the ARTS, it is helpful to draw comparisons and outline features. The engineer can perhaps best visualize the control cabin of a crane, road vehicle, or ship, and imagine what capabilities would exist if it could be (a) air-conditioned and lighted, (b) supplied with two-way intercommunication including TV monitoring, and (c) converted to an air-cushion vehicle. By contrast, the psychologist might visualize the ARTS as a well-designed, moving test laboratory capable of tilting and rotation for experiments on perception of direction, posture, and movement. To the physiologist, the ARTS can effectively be described as an air-conditioned tilt table operating in all axes with unrestricted movement and built-on instrumentation and power. Finally, to those concerned with aerospace operations, the ARTS is perhaps best described as a safe-to-use trainer-simulator suitable for personnel selection, training, and reindoctrination in a variety of 1 to 2 G movement patterns. It is less costly and operationally less difficult to fly than aircraft and space vehicles. Features of the ARTS include its additional capability for disorientation and controlled function studies, including vestibular disorientation, and its high-speed rotation and maneuverability.

In fact, the ARTS is a highly versatile turning and tumbling simulator with a physiologically wide range of angular velocities. It is possible, very simply, to place the man sitting inside it into any relationship with regard to earth's gravity, from a comfortable reclining position to the highly unusual face-downward position, or from a head-down position to any of a number of special positions such as those used for resuscitation. With any one of these positions used at the start, it is then possible to turn the ARTS in roll, pitch, yaw, or any combination of these, or to let it turn in random fashion. Any sequence of such rotations is possible, because the mode can be changed remotely while motion continues. Motion may be preprogramed, but if desirable, the vehicle may be brought quickly to a halt and the man examined, interviewed, or evacuated. Movement is slow or fast and reversible.

With such operational versatility a wide variety of indoctrination, training, selection, or testing runs can be programed for sensitive, tolerant, or insensitive subjects. Untrained men, on entering the research and training simulator, respond in different ways. Some show trepidation and are best exposed to short, slow demonstrations of inversion and other positions. Others require only to see the ARTS in motion and quickly respond to the different modes of slow rotation which they often attempt to describe in terms of their own background knowledge of motion and position. Men with experience in motion simulators, centrifuges, and aircraft flight perceive the ARTS

as a sophisticated vehicle and are interested in its performance and handling characteristics.

Experienced and inexperienced men appear to classify in three groups according to their performance in vehicles: the sensitive, the tolerant, and the insensitive to motion. Performance and motion sensitivity can be tested in the ARTS. Moreover, sensitivity or tolerance for one mode of motion does not necessarily carry over to all other types, and this can be demonstrated. There are profound subject-to-subject differences. Screening and selection are possible either for motion sickness or for disorientation. From the first run, such characteristics are often apparent. Initial exposure, therefore, is usually one of exploration and tolerance assessment, leading to acceptance or rejection of subjects for such reasons as physiologic responses, personal willingness, or medical advisability.

Subsequent re-exposure to tumbling and rotation makes it possible to compare responses, sensations, and performance with the findings on earlier occasions. Re-exposure may be of three kinds. First, subjects may be exposed again to the same patterns of rotation or "flight envelope" as before, and responses and performances can be quantitated and compared. Second, exposure may be to longer or faster "flights" with the same initial position, the same axis, and the same direction of rotation as before. Longer flights than those previously tolerated may become possible. Faster flights of the same duration may also be tried out and accepted. Third, exposure may be at the same rate and duration but in new or different starting positions. The number of possible sequences is very large, and experimental programs have so far been restricted to perhaps 40 different sequences. (See table XX.)

The following list outlines the experiments which are described in this report: (1) studies on disorientation; (2) effects of different tumbling rates and axes; (3) effects of heat and cold; (4) circulatory occlusion tests; (5) studies on control capability and performance decrements; (6) orthostatic deconditioning by water immersion: (7) studies on extended rotation; and (8) instrumentation and demonstration runs.

Table I sets out the timetable. Work was in two segments. Phase II-A was carried out in early 1967 before the ARTS was moved from its preliminary site. Phase II-B ran from November 1967 to May 1968, after the ARTS was moved to its present site.

Concise description of the available patterns of rotation in the ARTS is difficult because there are so many. Pesman (37) gives a simple introduction to the different modes of body rotation, using a pictorial representation. The present rotational modes of the ARTS are given in table XX, and future possibilities are given in table XXI. Hixson et al. (27) have developed a sophisticated, rigorous kinematic scheme for all forms of body motion, including those typical of the ARTS.

In selecting representative patterns to be used in test runs and in predicting the effects on men riding inside the ARTS, both engineering and physiologic considerations exist. The problem has been reduced to manageable proportions by using short runs of fixed duration at predetermined rpm's. It has been found in cardiovascular experiments at 3, 6, 12, and 24 rpm

TABLE I

Phase II timetable, 1967-1968

Schedule	Date
Test plan submitted and accepted	18 Jan. 1967
Equipment construction	1 Feb. 1967
First test run of phase II-A	2 Mar. 1967
Last test run of phase II-A	6 Apr. 1967
New building handover	Sept. 1967
Refurbishing, troubleshooting, and safety engineering	16 Oct to 9 Nov. 1967
First test run of phase II-B	10 Nov. 1967
Last test run of phase II-B	29 Apr. 1968
Impedance device proved out	15 May 1968

(and intermediate rpm's) that the largest changes occur at 3 and 6 rpm. Rotation at 48 rpm is beyond the level acceptable to our subjects and operating team, although the ARTS is capable of at least 60 rpm. Forward and backward pitch, left and right roll, and left and right yaw are examples of simple rotational modes. In our experience thus far, no major differences have been found because left was selected in preference to right, or vice versa. Pitch and roll, pitch and yaw, and yaw and roll are other rotational modes which we have studied extensively. They are achieved by prepositioning the sphere or the external drive at an angle of 45°, midway between the principal axes of rotation. The only two other modes of rotation which we have used extensively are (a) random and (b) roll and pitch and yaw. The former is achieved by continuously varying random input to the direction of the external drive motor while holding constant the rpm. The latter is produced by prepositioning the sphere orthogonally at a 45° angle to all three principal axes before commencing rotation. (Example: *Step 1:* Turn sitting subject half right. *Step 2:* Tilt subject to half reclining position. *Step 3:* Rotate ARTS in what would be pure pitch if no prepositioning had occurred.)

A description of the ARTS is given in the next section and is followed by an account of the experiments performed.

II. DESCRIPTION OF ARTS

The All-Attitude Air-Bearing Research and Training Simulator (ARTS) is a hollow airborne sphere (10 ft. in diameter) designed for tumbling experiments on man. It is constructed of fiber glass with two access hatches: one for the passenger or pilot and one leading into the hydraulic system compartment. It may be classified as a self-powered, closed-environment, one-man vehicle capable of random rotation in all three axes or controlled rotation in the pitch roll, yaw, or any combination of these axes.

In its original configuration, the instrument was known as the Rotational Flight Simulator (RFS) and was at that time capable of 2 to 16 rpm for up to 30 minutes with somewhat shorter duration for high rpm random tumbling. In its present configuration, polar and equatorial external drive assemblies permit unlimited duration of flights at up to 60 rpm in any axis.

Physiologic experiments are carried out in the moving vehicle by two-way voice communication, closed-circuit TV monitoring, remote control of ARTS rotation, remote triggering of occlusion blood pressure cuffs, and continuous multichannel telemetry from on-man transducer to the experimenters' console. Figure 1 shows the outside of the vehicle with an open access hatch and the equatorial driving motor assembly. Access to the polar drive is through a port in the pedestal shown in the bottom right of the photograph. For ease of orientation to the viewer, the three principal axes of the vehicle are denoted by colored bands, and the position of the subject within the vehicle is indicated by six black profiles of body position. In the standard reference position obtained in the configuration shown in the photograph, the subject is sitting facing the camera with his body axis in the vertical position.

The inside of the vehicle is furnished with a comfortable supporting seat having head, neck, shoulder, trunk, arm, leg, and feet supports and two independent restraining harnesses. Subjects wear safety helmets, a breathing mask, and goggles. They have access to a quick-acting harness release, a warning button, an auxiliary light, breathing equipment, and a sick bag. Figure 2 shows the interior furnishing of the subject's compartment of the vehicle.

All control and monitoring equipment is concentrated in a nearby operating area shown in figure 3. It consists of: (1) vehicle control equipment; (2) communications equipment including intercom and TV monitoring camera; (3) medical monitor's display equipment; and (4) multichannel strip-chart recording equipment including patch panels and calibration gear.

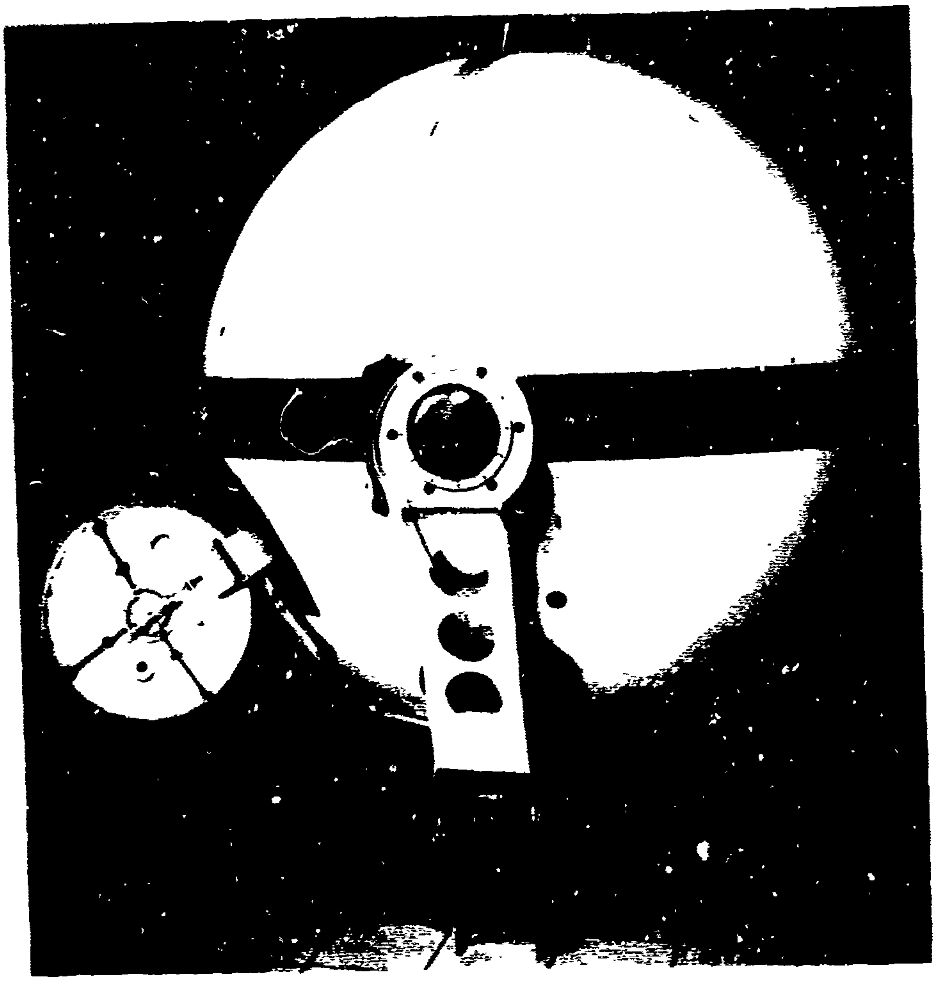


FIGURE 1

Outside view of ARTS.

Physiologic signals under routine study include heart rate, ECG, blood pressure by cuff inflation, respiration by heated thermistor, and rectal and skin temperatures. In addition, it is possible to monitor eye movements and blood pooling by using electro-oculography and impedance plethysmography. Equipment exists inside the ARTS for simple psychomotor tests including a number of displays and an all-attitude indicator. The subject has access to a control stick and can drive the ARTS using internal inertial drive rings situated in the principal axes of the ARTS. None of the last items are in regular use.

The history of the ARTS dates back to approximately 1965 when it was supplied in a single air-bearing configuration. At that time the vehicle was badly unbalanced and did not float freely on the air cushion. Its interior furnishings were removed and replaced, and the hydraulic controls and electrical equipment were rendered fireproof. Continuous research experience and concurrent engineering improvements have converted the vehicle to its present reliable research status. Engineering details of this work are given in section X and in an earlier status report (11).

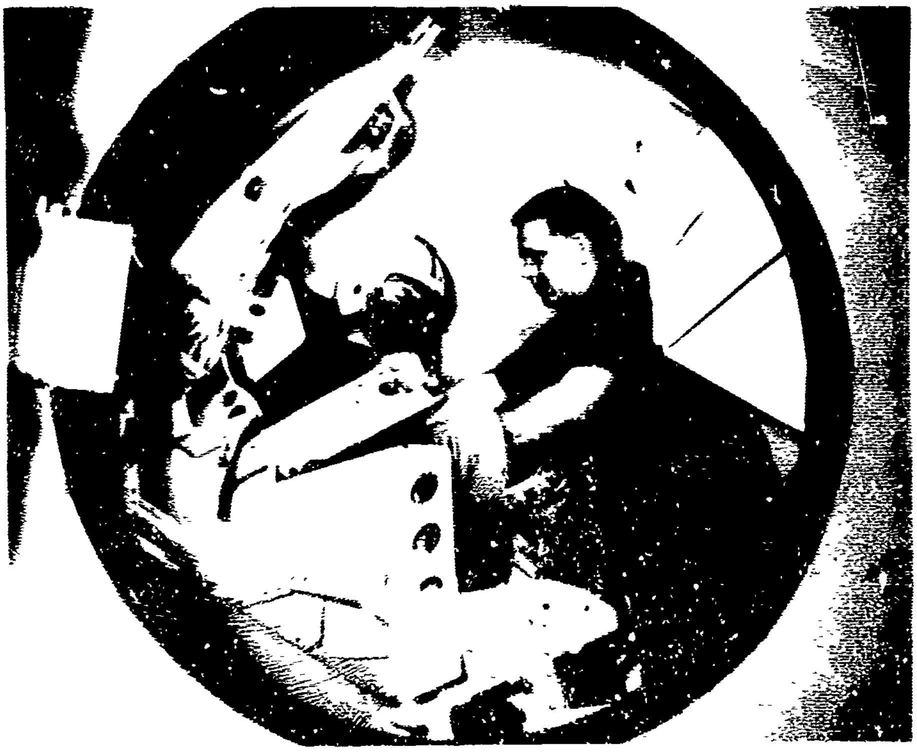


FIGURE 2

Inside view of ARTS.

The ARTS is currently in use for cardiovascular experiments. It also may be used for a wide variety of other physiologic experiments requiring electrical power, compressed gases, breathing gases, and such simple equipment as muscle dynamometers. An important additional area is its use for personnel monitoring and testing under stress. Tests on habituation, training, and performance are also to be regarded as routine procedures with the vehicle.

III. EXPERIMENTS ON OCCLUSION

The effects of posture on blood circulation are profound. When a man moves from the horizontal position to the vertical position, blood pools gravitationally into the dependent parts of his body and would accumulate there if it were not for reflex peripheral circulatory adjustments and an increase in heart rate and cardiac output. Under dynamic conditions, observed changes (11, 41) appear to be a function of both instantaneous posture and the speed and nature of body movement. Understanding the cardiovascular consequences of rotation and tumbling is essential in any attempt to explain and prepare for the eventuality of accidental tumbling in space and abolish undesirable circulatory effects due to change in posture or activity. Events encountered during tumbling in 1 G conditions have already been compared with the events believed to occur in 0 G ambient conditions (29).

The principal and most obvious cardiovascular consequence of tumbling is cyclical cardioacceleration and cardio-deceleration which occur during pitch, roll, or any combination of these types of rotation with some other axis rotation. Cardiac slowing is often very dramatic, being both profound and fast to develop. It has justifiably been related to the bradycardia of inversion and indeed may be called the bradycardia of tumbling. By contrast, the

FIGURE 3

Control and display console.

cardio-acceleration, which may also be profound, is slow to develop. At fast rpm's full development of the high heart rates may not be achieved; at slow rpm's tachycardia may be profound. Consequently, the rate difference between bradycardia and tachycardia of tumbling is rpm-dependent.

The precise mechanism by which these changes are produced is not clearly understood yet. Pharmacologic evidence on dogs during tilting suggests that the vagus reflex is responsible for the onset of bradycardia. A consistent finding in man is the extremely rapid development of bradycardia during tumbling. Lim and Fletcher (30) have described the significant features of sinusoidal stimulation imposed by tumbling in a 1 G field and were able to construct a hydrostatic pressure model for both arterial and venous components of the circulatory events. This model must be tested, and an explanation must be found for the large amplitude of the QRS complex which consistently develops at or near the head-up position and then diminishes cyclically. The influence of posture on the ECG is well-known (22, 33, 47), but its phase relationship in tumbling is not clearly explained.

Influence of blood distribution

To test the importance of an intact column of blood in the arterial and venous circulations, two 9-inch thigh occlusion cuffs were fitted to the legs of subjects prior to tumbling. Equipment included remotely controlled inflation and deflation switches and a pressure reservoir which produces a 4- to 5-second rise to 180 to 200 mm. Hg in the thigh cuffs. This increase in pressure bleeds off rapidly on deflation.

Two series of experiments were performed. First, 32 experiments were performed on 5 subjects to determine whether or not bilateral

thigh occlusion abolished the alternating bradycardia-tachycardia of tumbling. Second, 18 experiments were run on 4 subjects to determine what effects were produced when the blood was pooled in or drained from the legs by inflating the cuffs in different body positions before tumbling. Table II lists the experiments performed and shows that 45 successful experiments were achieved after 5 preliminary demonstrations of successful occlusion.

In the first series of tests, occlusion pressures were applied and released approximately ten times per subject at predetermined positions throughout the tumbling cycle. Runs were at 6 rpm, pitch forward, which is known to produce clearly defined bradycardia and tachycardia in most subjects. It was confirmed in additional runs at 6 rpm that pitch-backward tumbling produced similar results. In no case was the alternating fast-slow heart rate oscillation abolished. Bilaterally occlusive inflation of the thigh cuffs during rotation altered only the maximum heart rate, which increased for 5 to 6 seconds and then declined to a value somewhat less than the values before occlusion. Upon release of cuff pressure, there was again a transient change and the subsequent blood pressure level increased 5 to 20 mm. Hg above levels observed during the occlusion runs. No profound or consistent changes in electrocardiogram, heart rate, or respiration were observed on deflation; often there were no detectable changes whatever. Figures 4A and 4B show typical results of cuff inflation and deflation.

TABLE II

Experiments on bilateral thigh occlusion

Subjects: N.C., D.E., J.L., L.M., J.S., T.S., B.W., D.W.

Number of development runs: 5

Number of test runs: 45

Modes tested: Pitch forward

Pitch backward

Yaw

Pitch and roll

Range: 3-6 rpm

Method: Remotely controlled inflation or deflation of 9-inch thigh occlusion cuffs preplaced on both legs.

Typical results: Inflation or deflation during tumbling caused small transient effects only. Inflation prior to tumbling caused marked and prolonged effects which were strongly posture-dependent.

In the second series of experiments thigh-cuff occlusion was applied before the start of tumbling. The effects on heart rate and blood pressure depended upon the posture and the time of occlusion. In occlusion applied in the head-up position, subsequent heart rates in both bradycardia and tachycardia were lowered by 20 to 30 beats per minute and remained consistently at the new level (fig. 5A). On the other hand, in occlusion applied in the head-down position, subsequent rotation produced heart rates which showed a very large peak-to-peak difference between bradycardia and tachycardia (fig. 5B). Experiments in which occlusion was applied in the horizontal position were intermediate in their effect. It was concluded that the amount of blood redistributed to the central circulation or withdrawn from the central circulation governed the heart rates throughout tumbling and that the blood pressure effects of cuff inflation are transient in nature and small in magnitude whether applied in the steady state or during rotation.

Figures 6A and 6B show both inflation and deflation effects on the resting man, when the cuff was applied in the head-up position. Inflation caused a transient rise in heart rate; deflation caused a transient fall and was extremely small. No modifications were seen in respiration or in the electrocardiogram waveform. Blood pressure changes were also small.

Interpretation and significance

Consistent maintenance of heart rates 25 to 35 beats per minute above or below the normal resting value characterizes experiments with prior bilateral thigh occlusion. By contrast, when occlusion is applied during tumbling or rotation, the changes are small. There was no possibility that artifacts due to cuffs or to respiratory movements caused the results described. A relatively large volume of blood

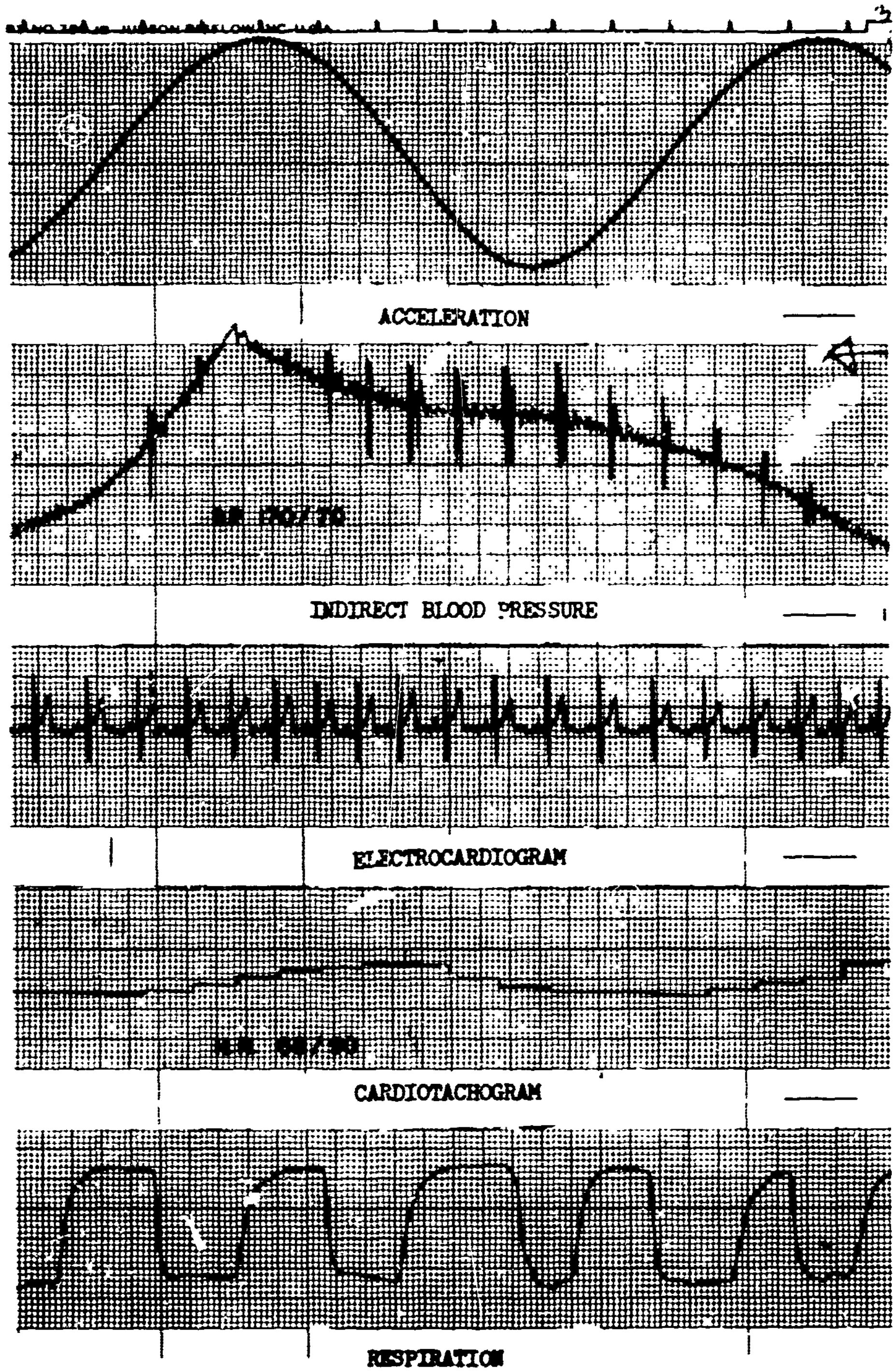


FIGURE 4A

Minor effects of cuff inflation during rotation. Subject D.W.; 15 Nov. 1967; pitch forward, 6 rpm.

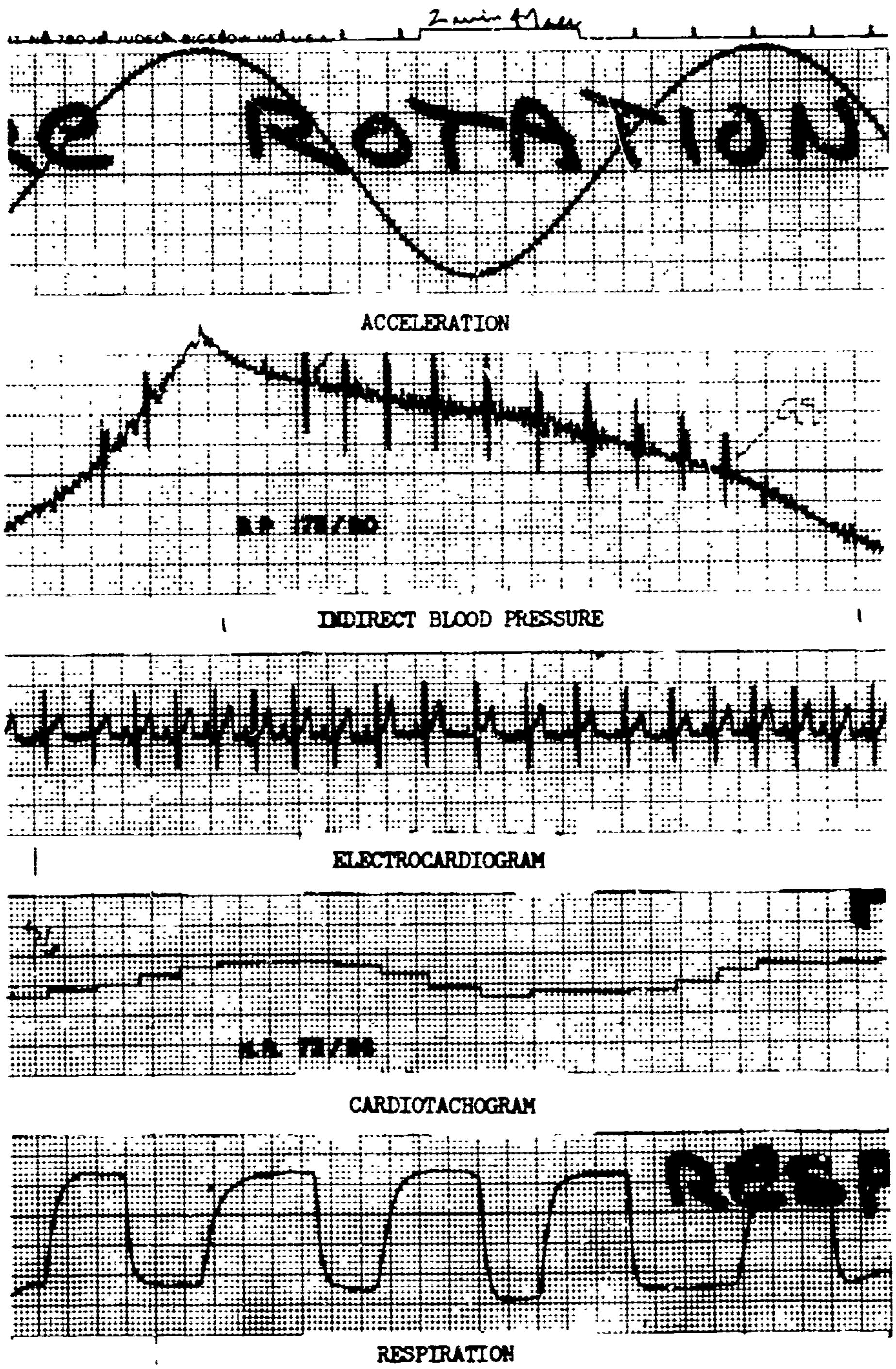


FIGURE 4B

Minor effects of cuff deflation during rotation. Subject and conditions same as in figure 4A.

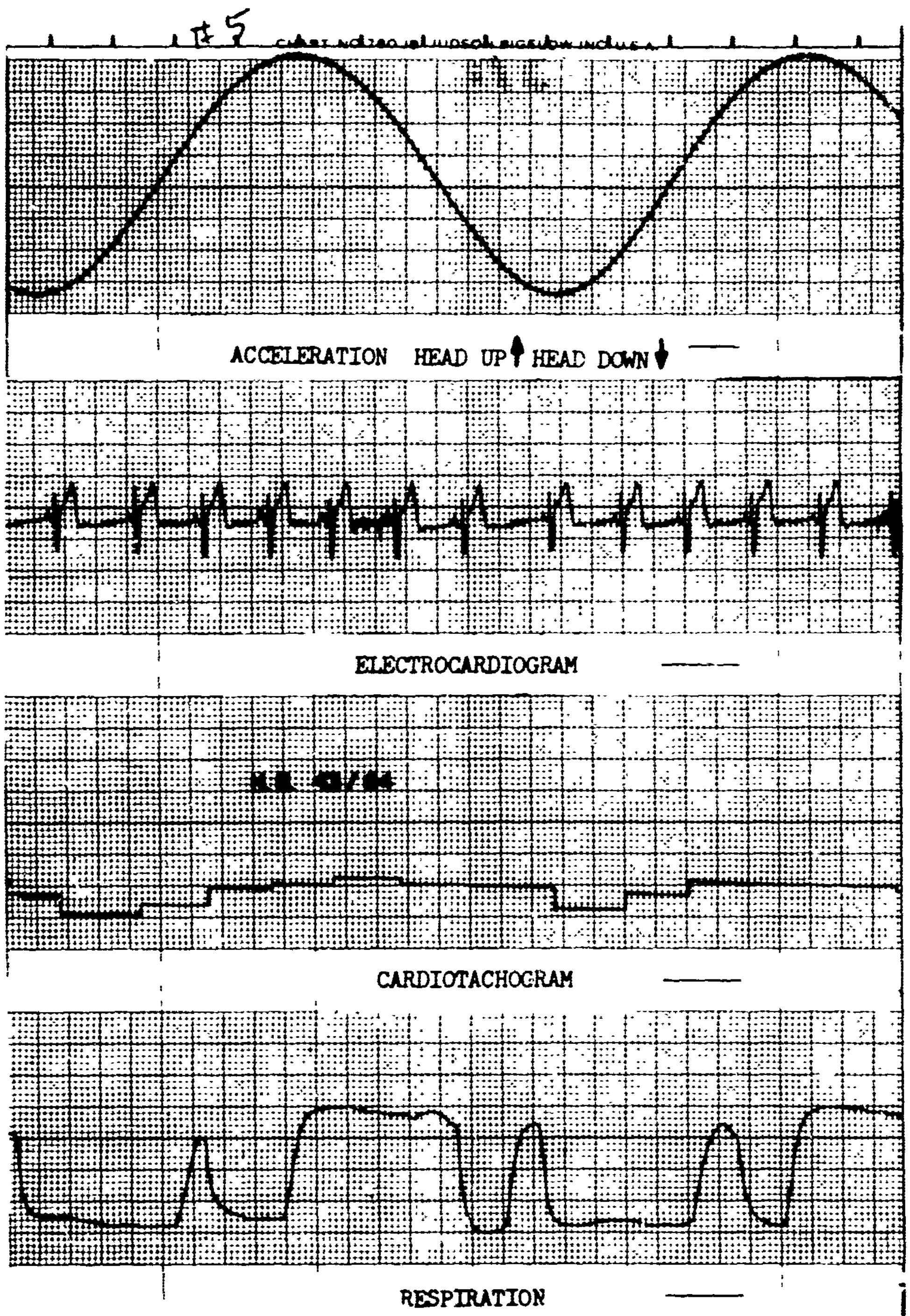


FIGURE 5A

Occlusion before tumbling in head-up position. Subject T.S.; 22 Nov. 1967; pitch; 6 rpm.

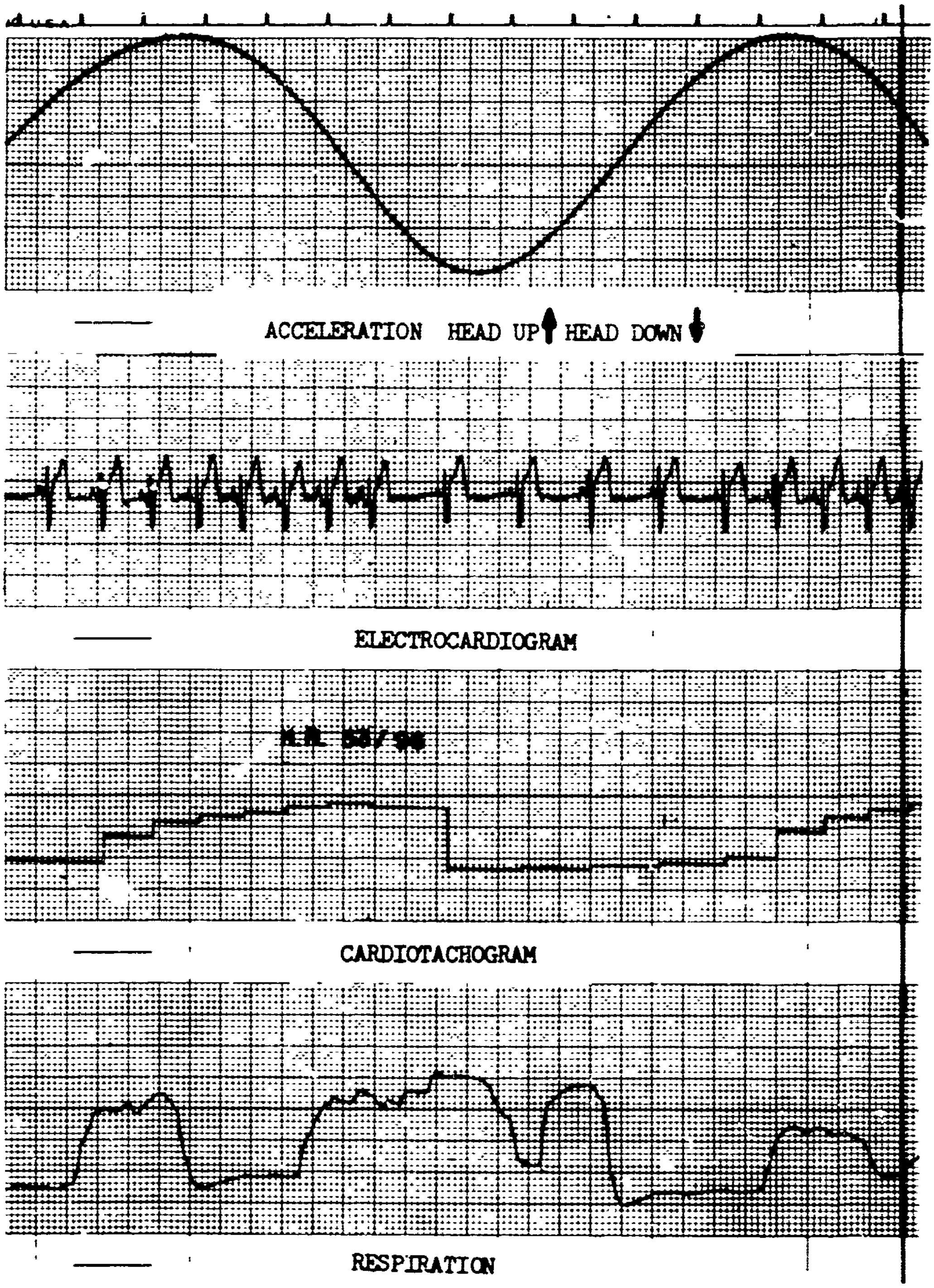


FIGURE 5B

Occlusion before tumbling in head-down position. Subject and conditions same as in figure 5A.

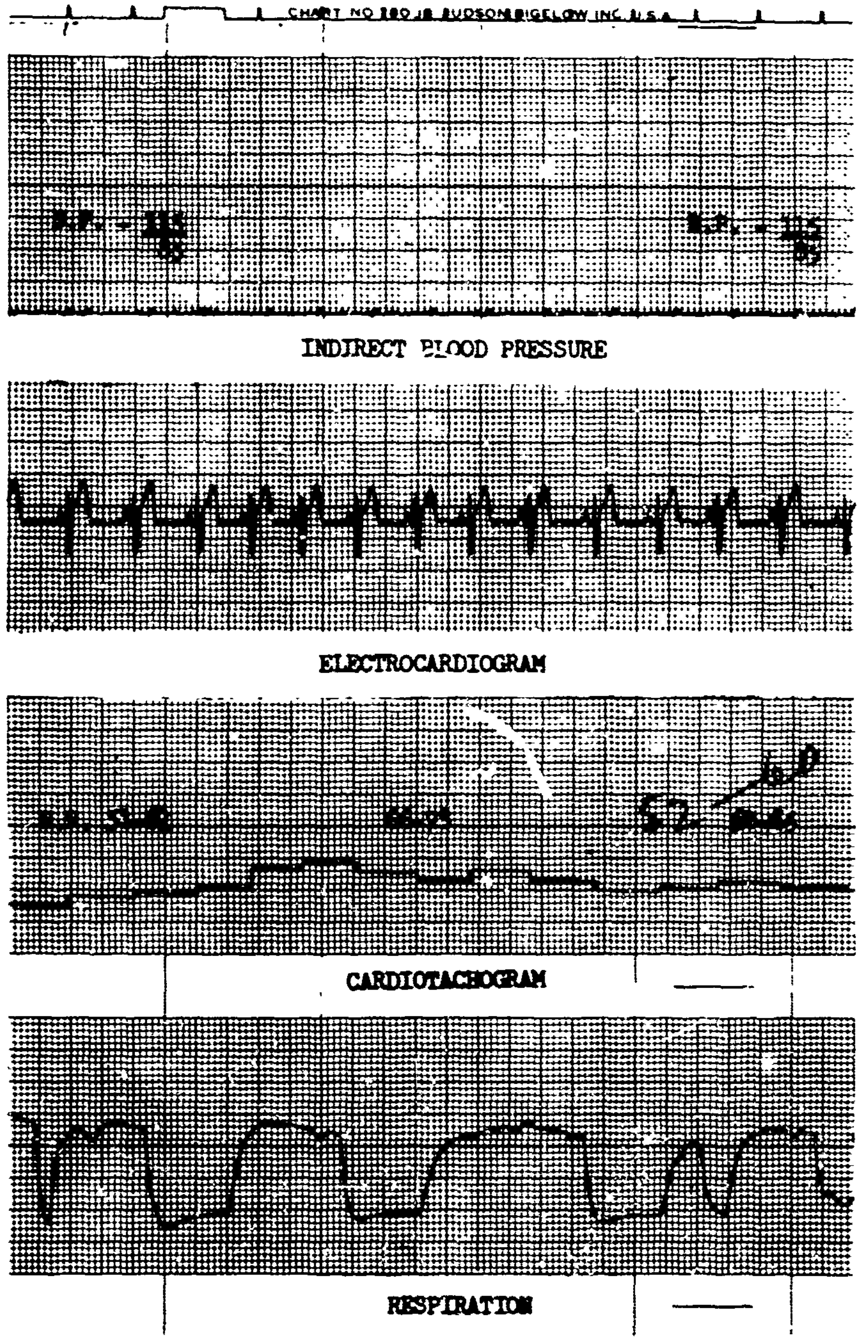


FIGURE 6A

Small transient effects of cuff inflation at rest. Subject T.S.; 22 Nov. 1967.

which is normally present in the legs is capable of being drained into the central circulation and modifies the level about which heart rate is controlled. Conversely, blood may be withdrawn from the central circulation and confined in the legs if cuffs are inflated while the

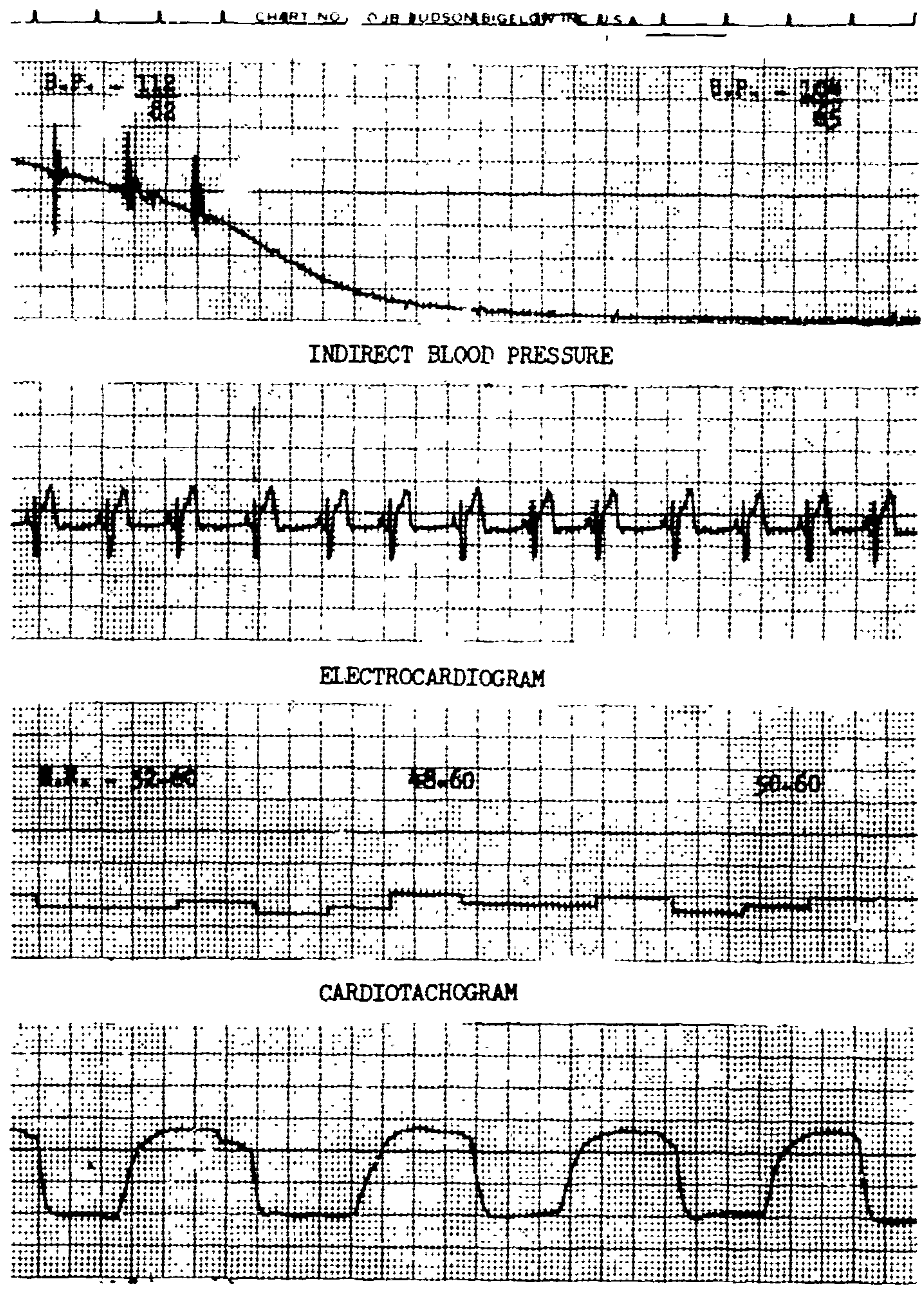


FIGURE 6B

Small transient effects of cuff deflation at rest. Subject and date same as in figure 6A.

subject is in the sitting posture before tumbling begins.

The first part of these investigations extends earlier findings with the ARTS and implicates volume or stretch receptors in the central blood and circulating system. At the same time, it reaffirms the important and very rapid regulating contribution of baroreceptors in the arterial circulation and perhaps also in the venous circulation during tumbling. The results extend our knowledge of circulation regulation and blood redistribution mechanisms in different postures (1, 17, 22, 33, 48, 54, 55, 59). They relate to our increasing knowledge of the function of stretch and volume receptors in the splanchnic areas (46), the pancreas (43), the central veins (16), and the heart (15, 26, pp. 227-229). Other workers have used extremity cuffs, leotards, and tourniquets (52, 53) and have worked on methods to reduce the gravitational effects on blood distribution (28). The importance of hydrostatic pressures in the vascular tree and the height of the venous column is recognized (5, 7). Mechanisms for storing blood in the capacitance vessels and for explaining the role of the stretch receptors in the arterial tree have also been described (4, 45). The importance of neurogenic control of the peripheral blood vessels is also known (40).

It was concluded that indirect blood pressure measurements during tumbling show only transient changes due to the application of occlusion, and the observed readings are well within the normal range of values seen in aviators (36). Circulating blood volume should be measured in different body postures and hopefully during tumbling. Only when additional data are available to show (a) continuous direct blood pressure records, and (b) central blood volumes, shall we be able to interpret the relative importance of blood pressure over volume receptor regulating mechanisms.

From the practical viewpoint, any situation which changes circulating blood volume (for example, ambient temperature, water deprivation, feeding dehydrated foods, orthostatic hypotension) may produce dramatic changes in heart rate. If a call to perform hard physical work occurs at the same time other forms of stress are applied, the cumulative effects may be additive and cause serious combined stress. In such cases, mission effectiveness and subject safety may well be prejudiced.

IV. EXPERIMENTS ON IMPEDANCE AND BLOOD POOLING

The conventional method for study of blood distribution involves a lengthy series of tests in different postures during which the total volume of blood is measured and partitioned in such body parts as the limbs and trunk, thorax and even the fingers, hands, and forearms. Most methods are inappropriate to the dynamic situation and studies in vehicles; therefore, it will be difficult to procure reliable estimates of the volume of blood being redistributed during tumbling at different rates and in different axes of rotation. The conventional water-filled plethysmograph, which is often used for volume determinations of forearm, hands, or fingers, is of course gravity-sensitive and would have to be replaced in the ARTS by an air-filled plethysmograph. An additional problem would arise in positioning the instrument which must be positively and tightly located on the arm in such a way as to eliminate movement artifacts.

More realistically, methods of estimating change might involve the use of rigid displacement or pressure chambers bolted inside the ARTS. Alternatively, the linear dimensions of a limb or trunk might be determined either with elastic air-filled tubes or with a mercury-in-rubber strain gage of the Whitney type. Most of such methods involve on-the-spot measurements by an observer and are unsuitable for use in the present single-man configuration of the ARTS. A technic is required that will give continuous readout which is insensitive to the earth's gravitational force, to vehicle vibration and inversion, and to the passive body movements imparted by the tumbling vehicle.

Impedance measurements in a rotating environment

Perhaps the most practical current method for use on a tumbling or rotating person is that

of impedance plethysmography. Figure 7 gives a schematic diagram of the instrumentation required for experiments of this kind. An oscillator with a frequency of 500 kc. or higher is used to provide an a.c. signal which is applied to two skin electrodes on the chest, arm, or leg. Reference electrodes, which usually include a large foil isolator for limb measurements and a chest band for trunk determinations, are used to pick up the radiofrequency signal transmitted through the tissue. The signal is modulated and amplified to give a d.c. level output and is fed to a pen writer or other signal recorder. Although the technic has been in use for 10 to 20 years, the relative impedances of blood flow and tissue movement are not yet known. However, changes in limb volume and in the volume of blood passing through tissue are detected as changes in impedance, and both slow changes (for example, blood filling or emptying) and more rapid changes (for example, respiratory movements) can be monitored. The technics and theory of impedance work are reviewed and discussed critically in comparison with other methods by Petersen in *Methods in Medical Research* (42).

Figure 8A shows the effects of tilting from the head-up to the head-down position on limb impedance, as recorded in the ARTS. Slow inversion (12 to 13 seconds) produced a rise in negative impedance, which developed to its full extent in approximately 26 seconds. Thus, the technic is of value in recording slow changes telemetrically in places where direct measurement is impossible. Figure 8B shows the application of this technic to the tumbling situation. Accelerometer output in the upper part of the record indicates instantaneous position during pitch-forward tumbling at approximately 8 or 9 rpm. The measured limb impedance is given in the lower tracing, a decreased volume indicated by an upward deflection. With such fast rotation it is not possible to develop the full impedance change of inversion. The rate of change of impedance may be realistic, however, in that it takes significant time for blood to redistribute. The phase lag in the impedance record indicates a time lapse of 1 or 2 seconds after the accelerometer output. The time taken for blood to redistribute may exceed the time available with all but very slow rpm's; therefore, the impedance record may be a true record of blood redistribution. This would be in accord with the findings of Allwood and Farncombe (1), who compared forearm impedance readings with forearm volume plethysmography measurements, using occlusion technic in 14 subjects. Pottier et al. (38) have recently shown that volume measurements in the feet are exquisitely temperature-sensitive.

Importance of further work

In view of the strong suggestion in the previous section about the importance of volume in blood redistribution under gravity, it

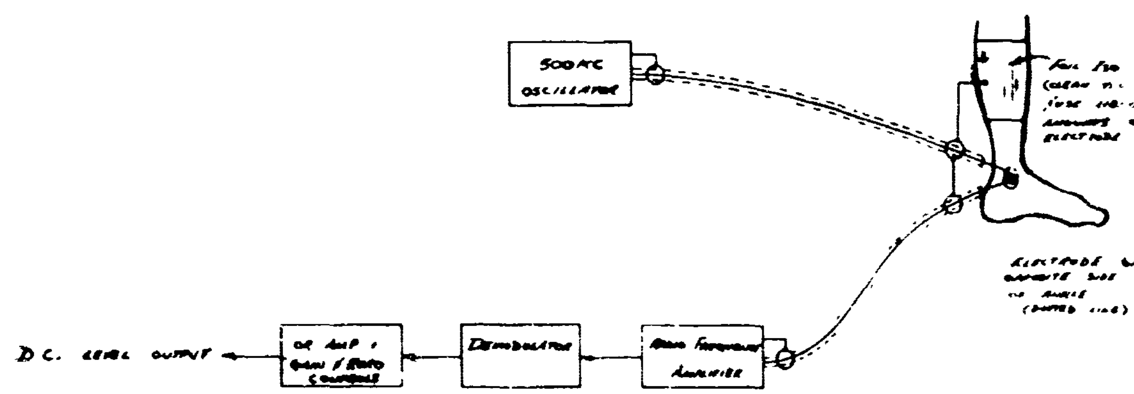


FIGURE 7

Schematic diagram of impedance instrumentation.

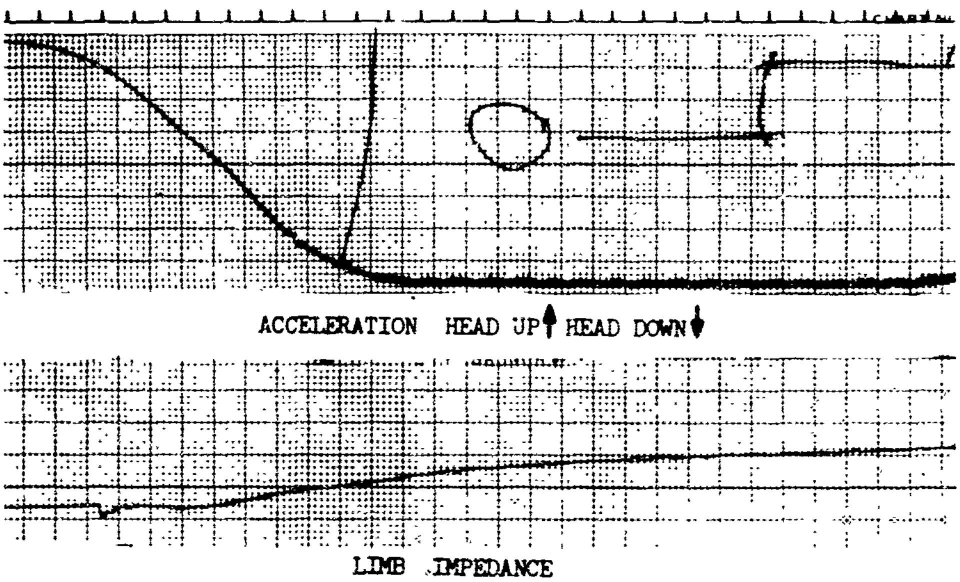


FIGURE 8A

Limb impedance changes due to inversion. Subject E.M.; 15 May 1968; pitch; 9 rpm.

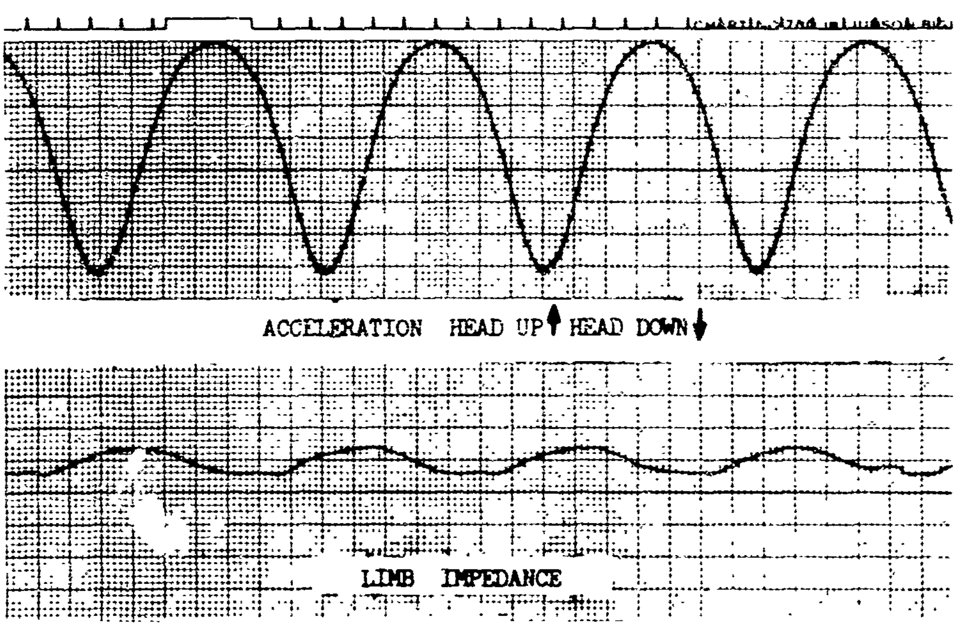


FIGURE 8B

Limb impedance changes due to tumbling. Subject and conditions same as in figure 8A.

is important that some method be devised of recording the time of onset, the rate of change, and the magnitude of blood redistribution during tumbling. A number of new technics are available for studying tissue dimensions (for example, ultrasonic scanning), and such methods may ultimately prove suitable for use in the ARTS.

For the present, clean impedance records (a) are obtainable without noise under moving conditions in the ARTS, and (b) give an indication of change due to gravitational reorientation. It is recommended that further studies be undertaken to explore such effects as limb occlusion, immersion and rotation in yaw vs. rotation in pitch, and so forth.

V. PHASE SHIFTS AND EFFECTS OF TUMBLING RATE

Past experience with tumbling

Useller and Algranti (51) and Weiss et al. (58) provided the basic information on tolerance to tumbling when they studied rotation up to 70 and 120 rpm, respectively, in normal men. Most physiologic experience is confined to much slower rotation and can be regarded as an extension of findings on the tilt table. Routine experiments must be performed at somewhat higher rates of rotation and tumbling, and different axis rotations must be compared.

For this purpose, the ARTS is an ideal vehicle. It can move up to 60 rpm in roll, pitch, yaw, any combination of these or in random movement. Moreover, the vehicle may quickly be transferred from one type of motion to another, and both fast acceleration and fast deceleration are readily reproduced. In contrast to the slow events described in connection with blood pooling, events during rapid rotation require special analysis and careful experimental recording.

The potential flight patterns using ARTS are very large in number and can only be sampled. The first step was to explore gradually increasing rates in the principal axis of rotation. The second step was to compare rotation involving body inversion (e.g., pitch and roll) with rotation not involving such inversion (e.g., yaw and spit). This section represents totally new experience in the exposure of men to different varieties of dynamic stimulation.

Patterns and responses

Table III sets out details of subjects, test runs, flight durations, and rotational velocities. Eleven subjects were studied in 51 different test runs. Ten different rotational modes are listed, of which the last two require description. The term "turntable" is used to describe that form of rotation in which the subject was first rotated until he lay horizontally on his back and was then rotated about a vertical axis passing through his pelvis at right angles to the principal body axis. The motion resembles

TABLE III

Experiments on phase shift and effects of tumbling rate

Subjects:	D.B., G.C., N.C., E.D., D.E., J.F., F.H., S.H., J.N., J.S., T.S.
Number of test runs:	51
Modes tested:	Roll
	Pitch
	Yaw
	Random
	Roll + pitch
	Roll + yaw
	Pitch + yaw
	Roll + pitch + yaw
	Turntable
	Spit
Duration:	30 sec. to 12 min. 13 sec
Rate:	2, 4, 6, 10, 12, 14, 18, 20, 24, 30 rpm
Findings:	Highly significant differences between rotational modes (e.g., rotation in spit or turntable positions vs. tumbling in pitch or roll) and between rates, for example, of 6 and 24 rpm

that obtained when a man lies on a revolving turntable. The term "spit" is used to describe a rotation obtained by first tilting a man onto his back, with subsequent rotation about an axis coinciding with his principal body axis. It resembles the rotation of an animal on a spit.

Rotational velocities ranged from 2 rpm to above 30 rpm. Beginning subjects cannot tolerate high rpm's and rapidly become disoriented and sick above 6 rpm unless carefully exposed to a graduated program of runs. By contrast, experienced men easily tolerate much higher rotations and commonly report that disorientation is more serious between 6 and 12 rpm than at higher rpm's. However, even fully experienced men do not tolerate rpm's in the high 20's and low 30's for prolonged periods without special training.

Physiologic events are clearly rpm-dependent. Comparison of the onset of circulatory and other changes with the rate and position of rotation allows analyses of phase shift. These are potentially very valuable in exploring new physiologic parameters. Figures 9A and 9B show typical records at 6 rpm in two subjects. Figure 9A shows the effects of pitch and figure 9B, the effects of roll. Both forms confer sinusoidal gravitational stimuli and cause cyclical variations in heart rate. Variations obtained in pitch and roll are virtually indistinguishable so far as heart rate is concerned, but there is a strong suggestion that the ECG waveform may differ. It is not known whether or not the respiratory pattern changes, but there is the possibility of a pitch-roll difference in the records of respiration in figures 9A and 9B.

Forms of rotation in which there is no sinusoidal or other gravitational changes due to inversion produce much smaller heart rate oscillations. Figure 10 shows records obtained in 2 subjects in spit and yaw rotation at 6 rpm. Heart rate changes are tiny. ECG waveforms may not be significantly different, but there is a prospect for further useful analysis. Respiratory waveforms appear similar. The findings that steady heart rates are continuously maintained suggests that no major respiratory influences are in operation: deep breathing and breath-holding patterns are known to cause bradycardia and tachycardia.

Figures 11A and 11B show the differences between moderate (15 rpm) and high (30 rpm) rotation in pitch recorded in the same subject. Figure 11A shows 15 rpm with a slow paper speed. Heart rates moved in the range 81 to 104 beats per minute in synchrony with the vehicle movement. The higher rotation shown in figure 11B, having a much faster paper speed, shows that the cyclical oscillation in heart rate is almost abolished. It is difficult at this rpm to show that any synchronous bradycardia-tachycardia is in operation during the tumbling cycle. At rotations above 30 rpm even smaller rate differences are sometimes observed. Some subjects occasionally find it convenient or comfortable to breathe synchronously with rotation and inversion with the ARTS. Figures 12A to 12D show an experiment at 18 rpm in which the breathing pattern was almost precisely in synchrony with the inversion cycle. In contrast, the other run shows the same man breathing at a higher rate in a later test. Whether or not the respiratory pattern adds to the heart rate change is seen in figure 12B. Low excursion respiratory movements do not significantly change the heart rate. There is no visible difference in the records between synchronous and asynchronous breathing.

In strong contrast, both heart rate and respiratory waveforms are altered during rapid acceleration and deceleration. Observed changes are illustrated in figures 13A and 13B. Figure 13A, from right to left, shows that as the ARTS rotational velocity builds up from 0 to 30 rpm, the heart rate oscillations progressively diminished; whereas they were synchronous with ARTS oscillation at low speeds, they become asynchronous at higher speeds. Figure 13B shows dramatically the effects of sudden stopping of the ARTS. This record was made at two chart speeds in order to condense protracted events in a single diagram. Thus, the record on the extreme right of the diagram was taken at fast paper speed and shows the concluding events at 30 rpm. As the ARTS slows (shown

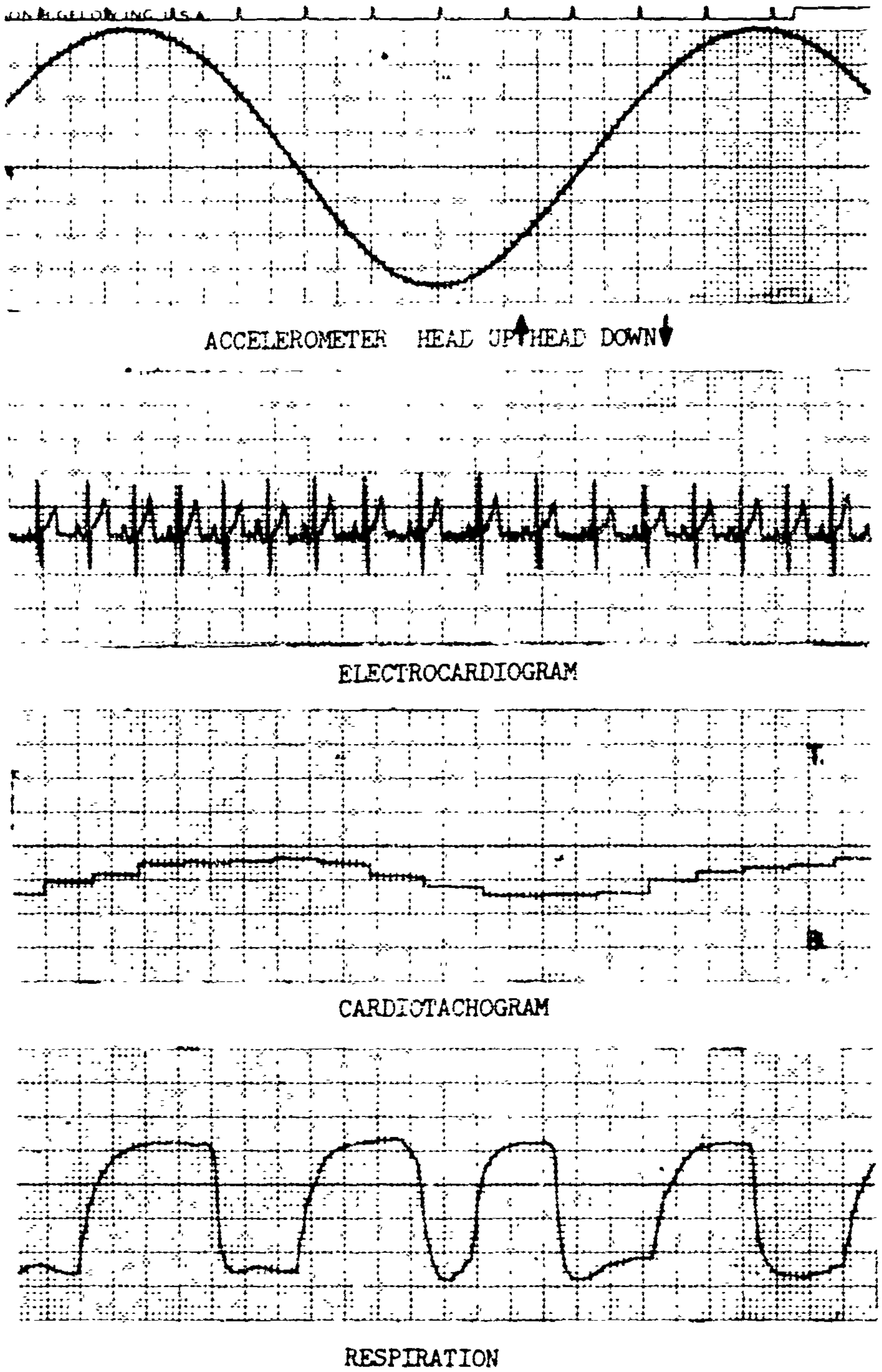


FIGURE 9A

Typical records in pitch at 6 rpm, showing gravitational pooling effects on heart rate. Subject D.W.; 15 Nov. 1967.

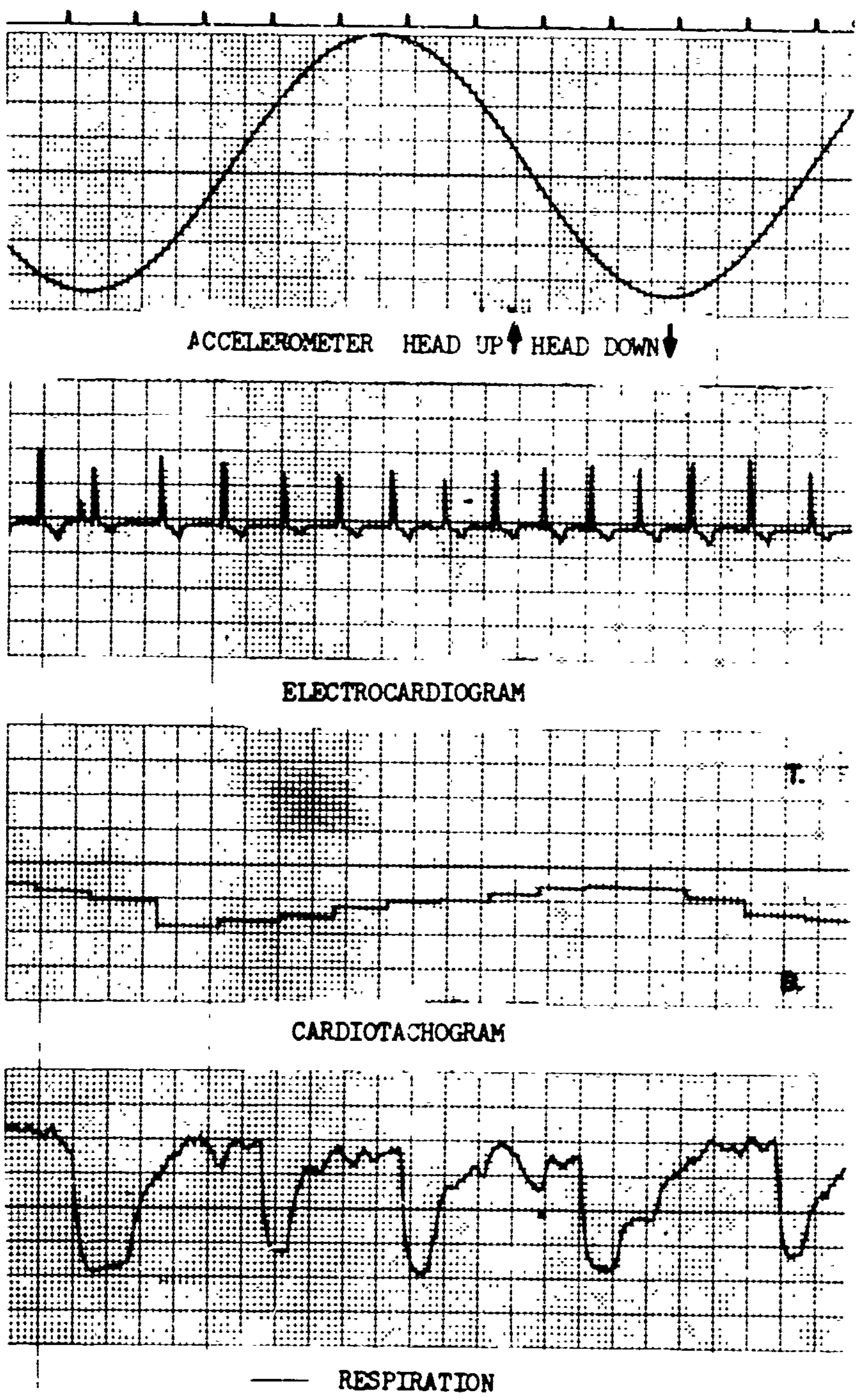


FIGURE 9B

Typical records in roll at 6 rpm, showing gravitational pooling effects on heart rate. Subject E.M., 28 Feb. 1968

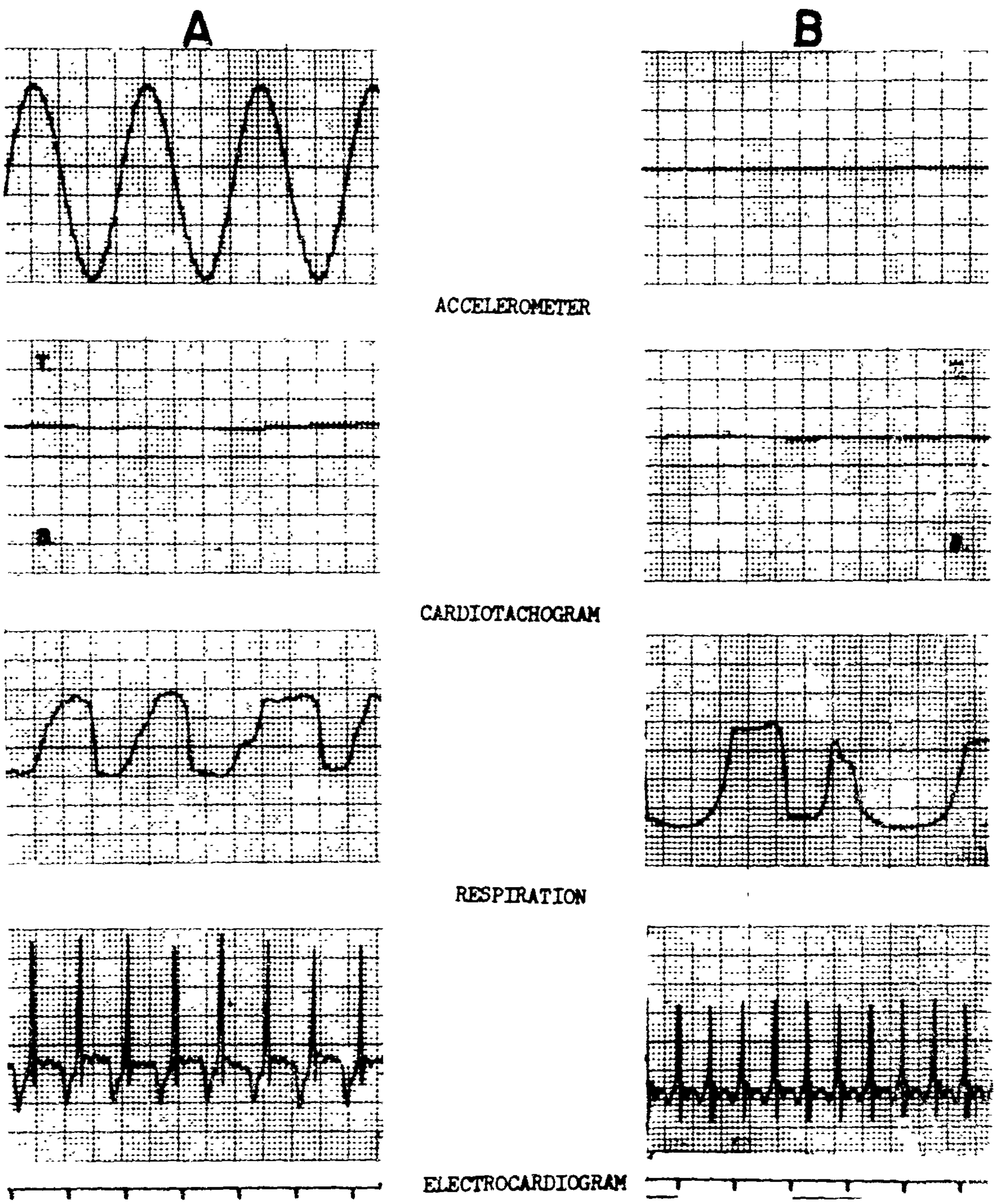


FIGURE 10

Typical records showing tiny heart rate changes in absence of oscillating gravitational pooling. A. subject J.F.; 20 Mar. 1968, spit; 30 rpm. B. Subject D.S., 6 Mar. 1968; yaw; 30 rpm.

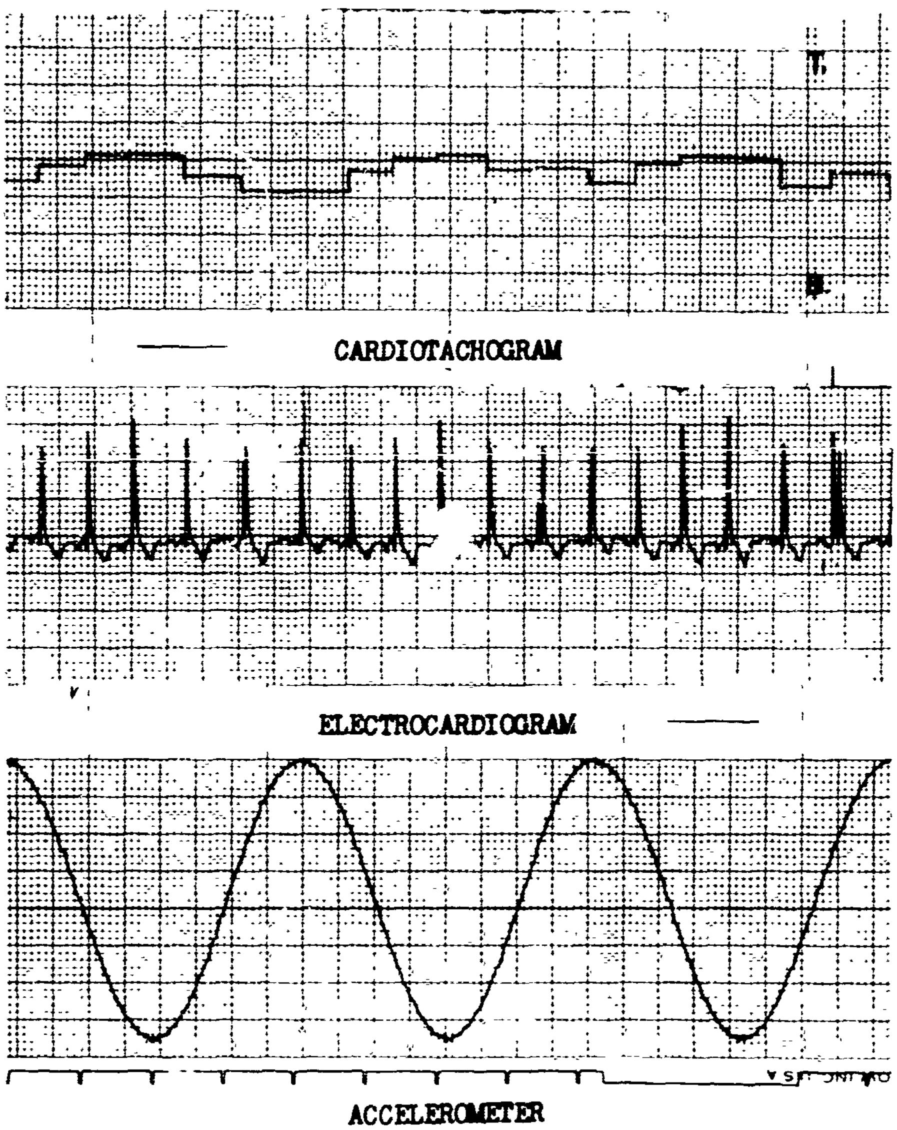


FIGURE 11A

Effects of moderate (15) rpm in pitch on ECG and heart rate. Subject E.O., 27 Feb. 1968.

toward the left of the diagram), paper speed slows and accelerometer output shows progressively slower rotation. Tachycardia-bradycardia cycling, which had been virtually abolished at 30 rpm, gradually is restored. Respiratory waveforms show that rather rapid shallow respirations converted to deep slower respirations as the ARTS slowed. Phase shifts may be analyzed in such diagrams. There is a clear case of heart rate changes taking place in anticipation of top dead center and bottom dead center in the ARTS rotation pattern.

These and other experiments at 2, 4, 6, 10, 12, 14, 18, 20, 24, and 30 rpm show clearly that (a) highly significant differences exist between the different rotational modes and (b) the rotational velocity exerts critical influence on heart rate.

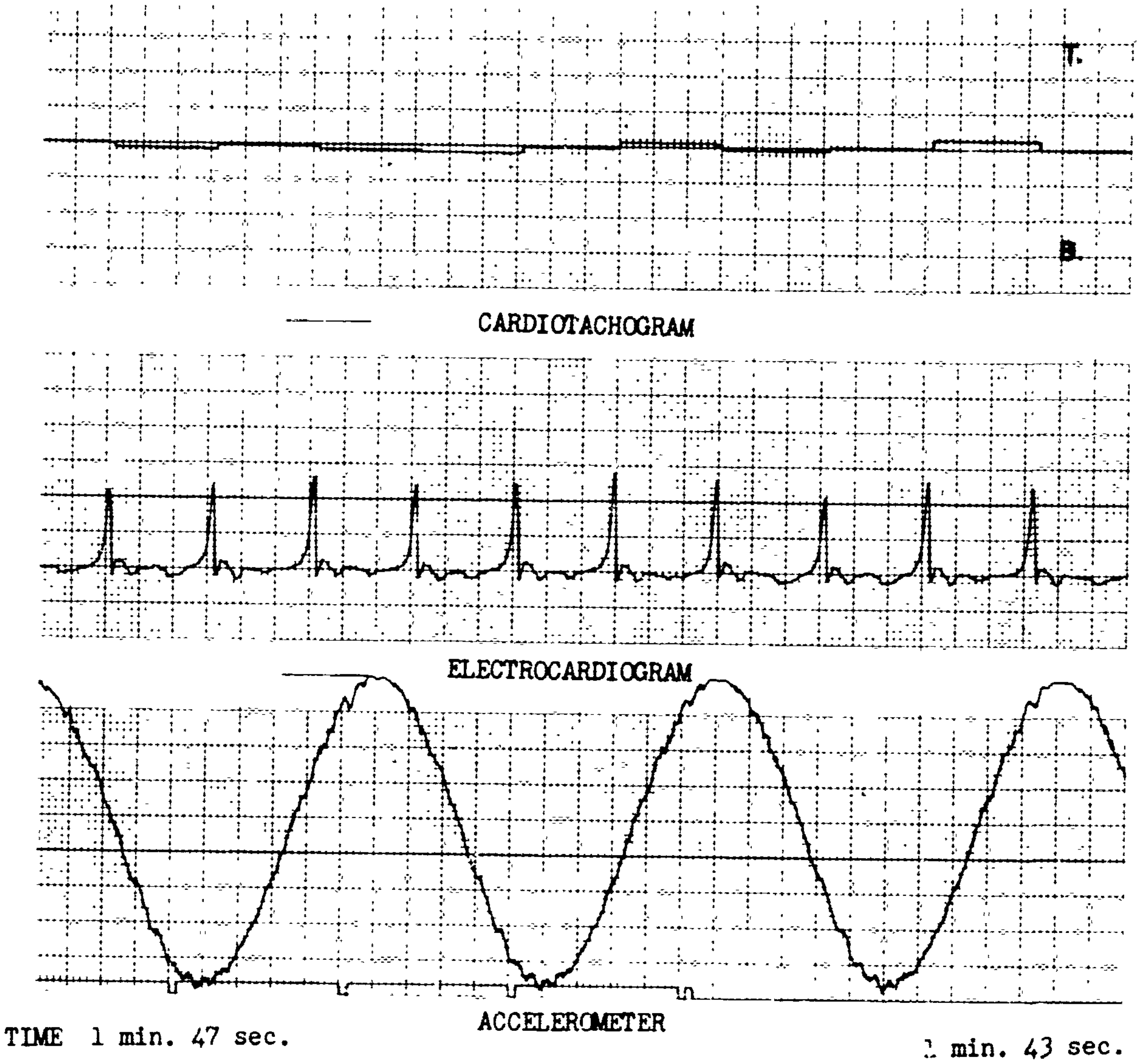


FIGURE 11B

Effects of high (30) rpm in pitch on ECG and heart rate. Subject E.O.; 2 Apr. 1968.

Interpretation and importance

As an analytical tool for physiologic research, the ARTS is probably unique. It is possible to condition the air within the sphere, thereby eliminating spurious temperature effects on heart rate and breathing, and to control the rotational rate in meaningful physiologic ranges in all forms of rotation. Currently obtainable rates of rotation exceed the limit tolerated by most subjects, meaning that the vehicle is capable of operating sufficiently fast to stress human circulatory mechanisms either alone or in combination with control temperature changes. The potential for further exploration of these dynamic changes is considerable.

The human electrocardiogram during tumbling shows at least two waveform modifications. First, the height of QRS complex

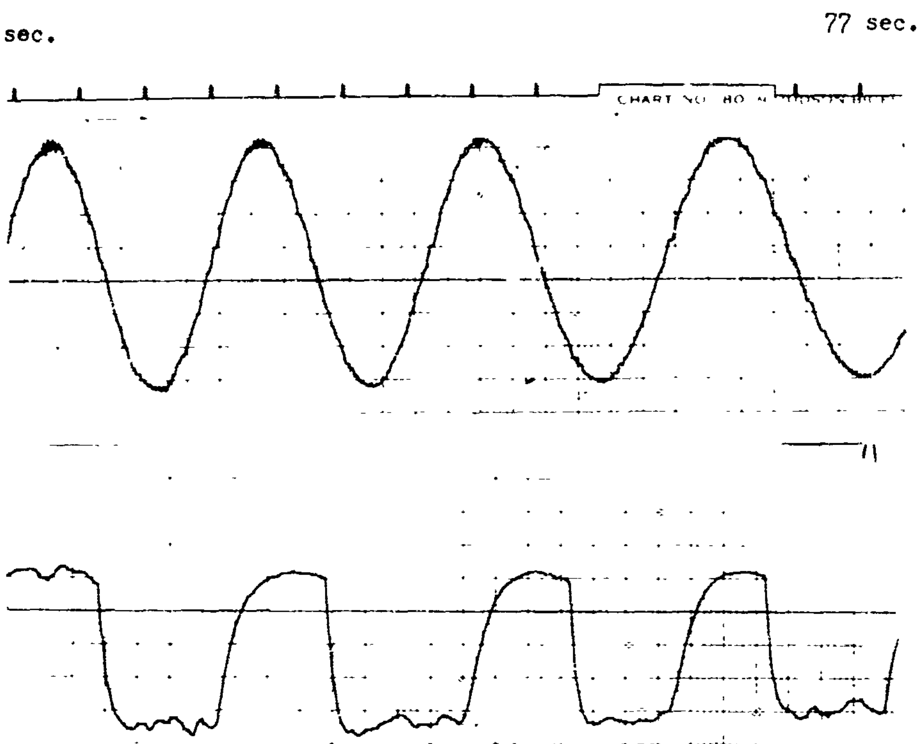


FIGURE 12A

Breathing in-phase with 18-rpm rotation. Subject T.S.; 9 Apr. 1968; pitch.

increases before or at bottom dead center (head-up), and these events require critical vectorcardiographic interpretation (32, 33, 47, 57). The relationship between the axis of rotation and the position of the body differs in animals and erect man, and this has significant physiologic consequences (6). A review of the central control of cardiac function has been given by Schaefer (44), and the different cardiovascular effects observed in various axes of rotation have been anticipated but not yet described in papers such as that by Urschel and Hood (50). The importance of the height of the blood column on heart rate has been anticipated (30), but complete analytical treatment requires careful experimentation on the ARTS and perhaps the centrifuge. Possibilities are exciting for increased understanding of cardiac and peripheral vascular control.

VI. EFFECTS OF HEAT AND COLD

Thermal and biodynamic stress combinations

Peripheral blood circulation is highly sensitive to air temperature. In conditions where body heat is being lost to the ambient air, skin vessels constrict and the cooled blood therein is returned to the central circulation. By contrast, when body heat production exceeds heat dissipation to the atmosphere, blood is diverted to the skin vessels and skin temperature rises. Under more extreme temperature conditions, shivering occurs in the cold and sweating occurs in the heat. Relatively small changes in air temperature are sufficient to produce large volumes of blood redistribution, and this is potentially important in designing

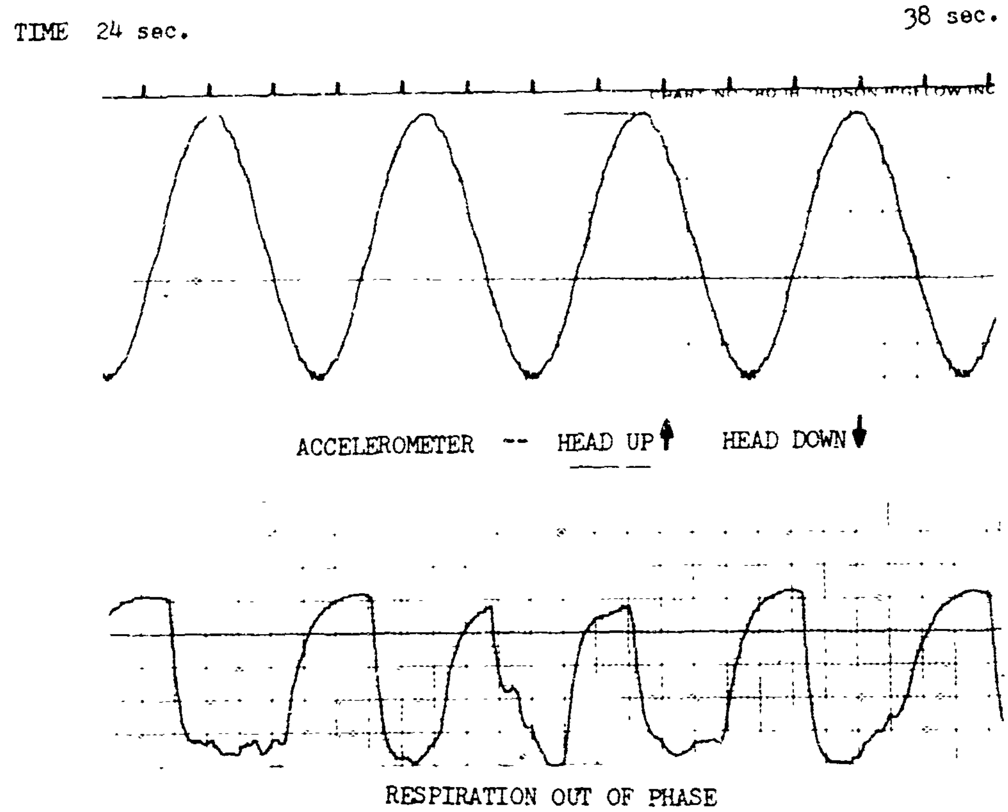


FIGURE 12B

Breathing out-of-phase with 18-rpm rotation. Subject and conditions same as in figure 12A.

temperature controls for vehicles. It is fortunate that, except for persons whose thermal acclimatization status differs from the norm, there is much uniformity in the upper and lower limits of the comfort zone. Marked differences from the usual comfort zone commonly occur only with changes in metabolic activity and thermal insulation of clothing.

By unintentionally changing the ambient temperature in such a way as to bring about vasoconstriction or vasodilation, it is possible to change the heart rate and to impose unwanted stress on the cardiovascular system. The combined stresses of heat and tumbling are potentially important in space, where extra-vehicular activity in a radiant heat environment might produce either excessively high heart rates or dangerously extreme vasodilation. It is important to know whether cooling provides any protection in this eventuality and whether there is an optimal environmental temperature so far as tumbling stress is concerned.

Equipment and procedures

Two sets of experiments, each with its control series, were performed. In the first series the ARTS was preheated to a selected temperature in the range 100° to 113° F. before allowing the subjects to enter, and the temperature was maintained while subjects were rotated, pitch forward, at 6 rpm for 3 to 5 minutes. In the second series the ARTS was precooled for 2 to 3 hours to 55° to 58° F. before allowing the subject to enter. Seven men took part in the series involving heat, and 5 men took part in the series involving cold. Subjects wore short-sleeved, loose surgical suits with low

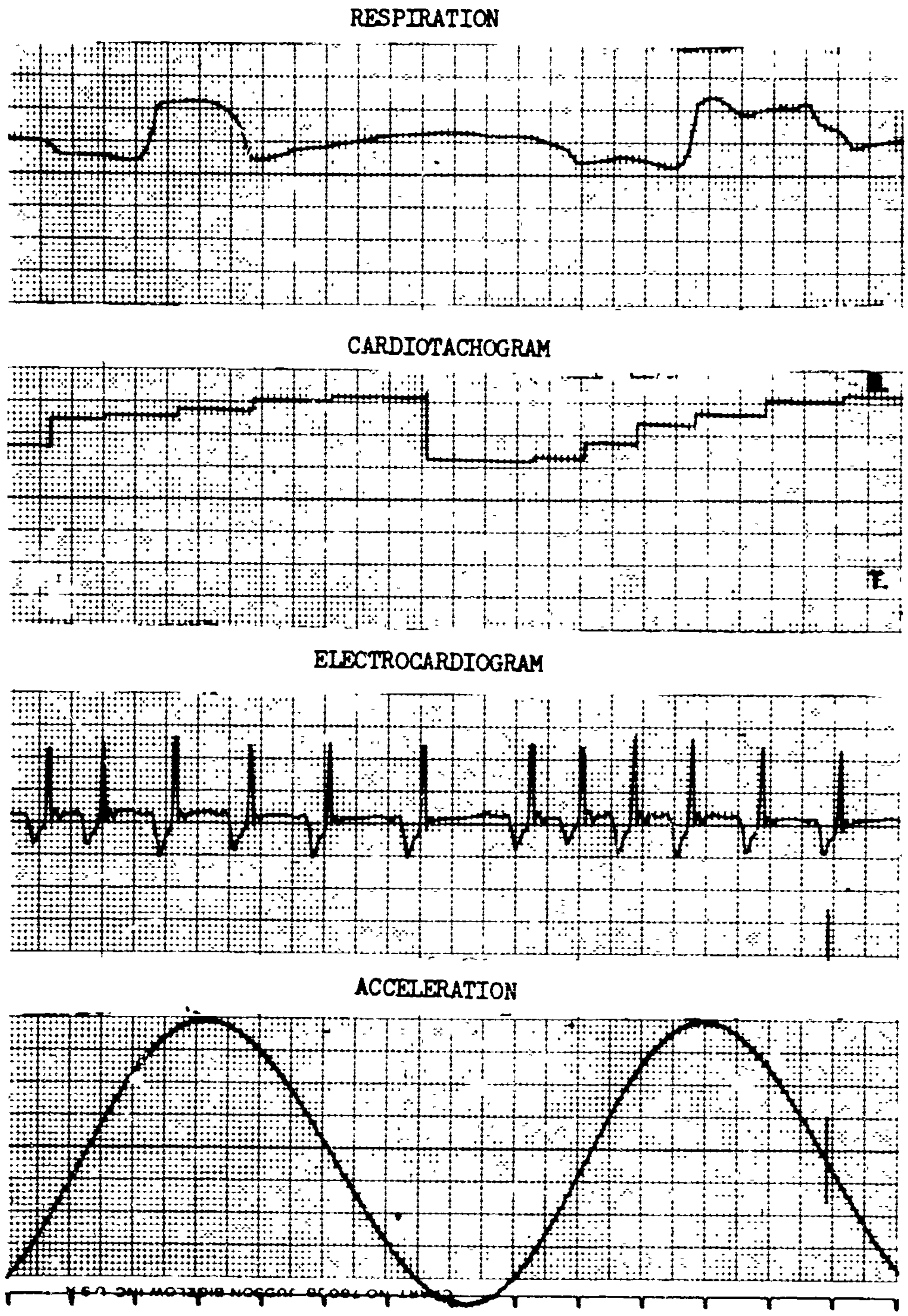


FIGURE 12C

Breathing in-phase with 6-rpm rotation. Subject and conditions same as in figure 12A.

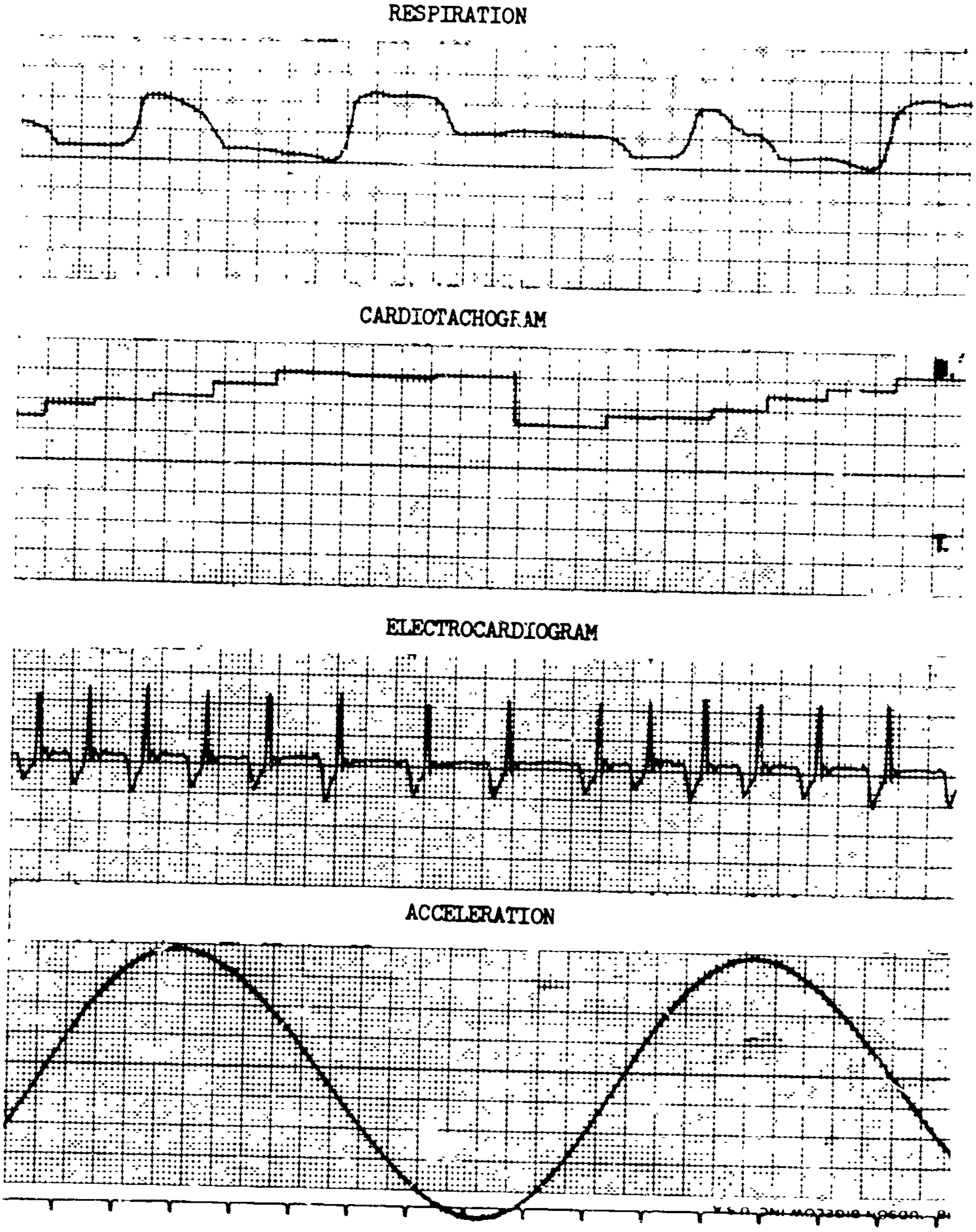


FIGURE 12D
Breathing out-of-phase with 6-rpm rotation Subject and conditions same as in figure 12A

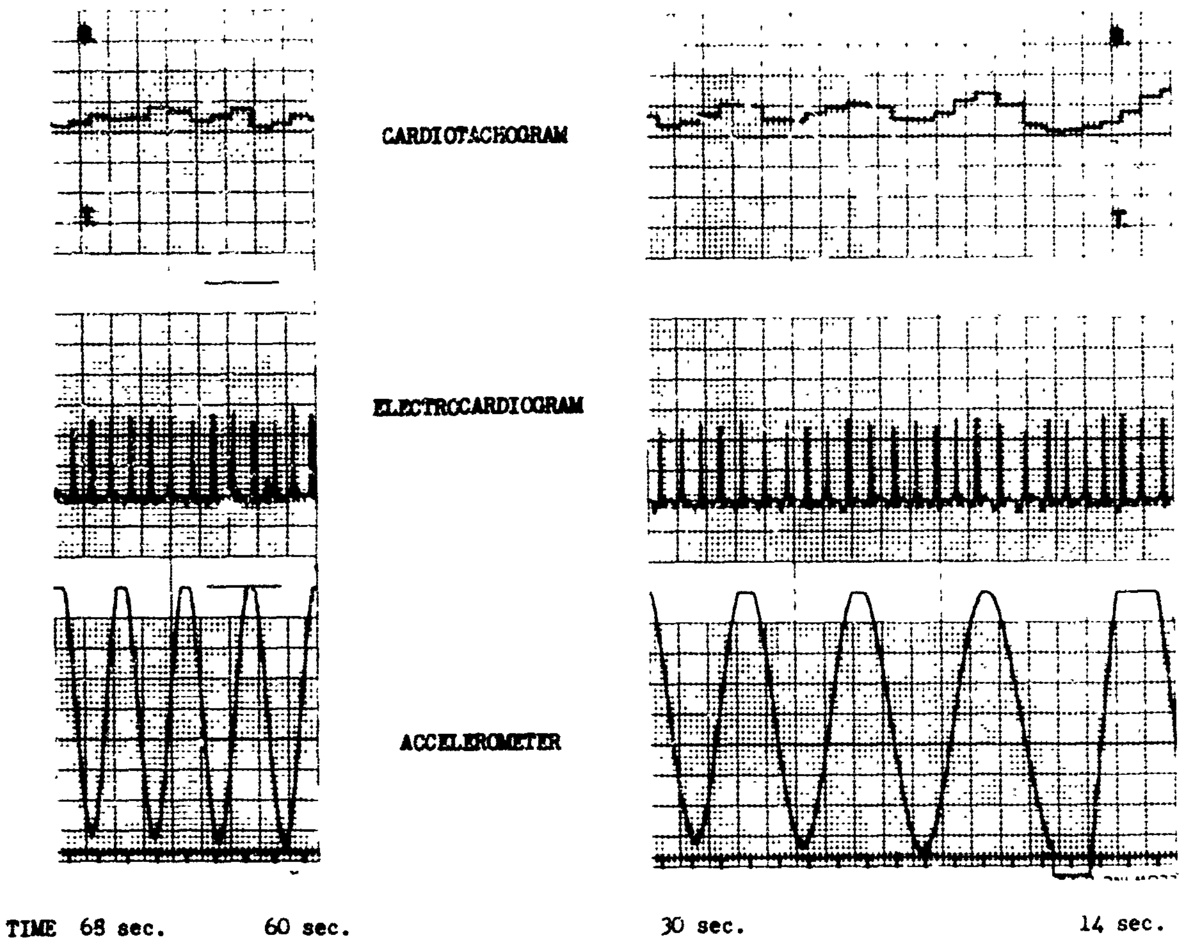


FIGURE 13A

Heart rate changes due to ARTS acceleration. Subject E.O.; 2 Apr. 1968; pitch; 30 rpm.

insulation values and were resting-sitting with low metabolic heat output before each test run. At least 2 hours had elapsed since their last meal, and the immediate response to eating had presumably subsided. Table IV summarizes the experiments carried out and the rotational patterns used.

Findings and conclusions

General results of the hot and cold runs are given at the bottom of table IV. During the hot experiments, only subject D.E. sweated significantly, but all subjects were vasodilated. During the cold experiments the subjects felt chilly but were not shivering. Four of the subjects felt the onset of nausea in the hot environment, but they tolerated the cold environment much better. In the heat, the average skin temperature increase was 3° F., and the skin was flushed warm and dry or just moist with perspiration. Skin temperature decreased by 2° F. (average) in the cold with evidence of dermal vasoconstriction. Rectal temperatures remained stable.

Resting heart rates increased approximately 12% in the heat and decreased about 8% in the cold. During rotation the heart rate

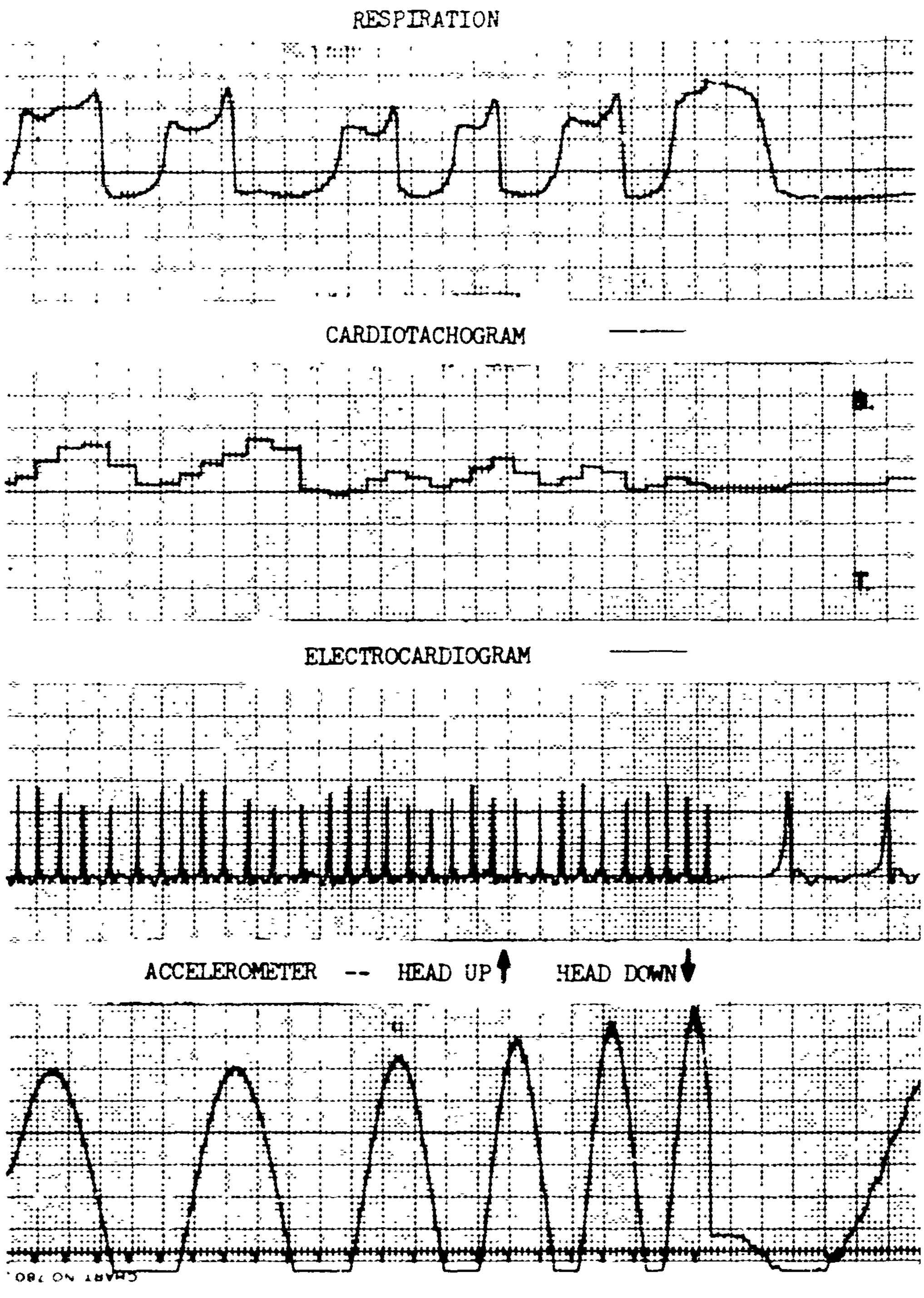


FIGURE 13B

Heart rate changes due to ARTS deceleration. Subject and conditions same as in figure 13A.

TABLE IV

Experiments on heat and cold

Hot	Cold
7 subjects	5 subjects
26 hot runs (96° to 113° F.)	4 cold runs (56° to 58° F.)
11 control runs (80° to 85° F.)	5 control runs (70° to 72° F.)
5 warm runs (90° to 92° F.)	1 cool run (66° F.)
Pitch, random, yaw	Pitch, random, yaw
6 rpm	6 rpm
Large bradycardia-tachycardia difference in heat; slower onset of bradycardia.	Small bradycardia-tachycardia difference in cold. Rapid onset of bradycardia with brief phase lag

tracked the body position as previously described (11, 29, 30) and displayed the characteristic sine wave pattern. Figure 14 shows the characteristic heart rate responses during typical hot and cold experiments and in a control experiment at a comfortable intermediate temperature. Blood pressures did not change significantly in any of these conditions, although the diastolic pressure tended to be elevated in the cold experiment. The respiratory changes were not correlated with either temperature or rotational stress. ECG's remained normal, and there were no extrasystoles or conduction abnormalities.

Figure 15A shows tracings of the cardiotachogram, electrocardiogram, blood pressure record, and accelerometer in a control experiment at 84° F. ambient temperature in comparison with a similar record (fig. 15B) made at 102° F. It is clear that the heart rate fluctuations were similar in range and average value in the two cases, although blood pressure was elevated in the heat as compared with control temperature.

Figures 16A and 16B show similar runs in a cold experiment. The range of heart rates was considerably smaller in the cold at 57° F. than in the controlled temperature of 70° F. The relative stability of heart rate in the cold is in contrast to that previously shown in the heat.

Comfort and thermal sensations have recently been reviewed again by Gagge et al. (14), and the associated physiologic responses at various ambient temperatures have been described. At temperatures which fall below or above the comfort zone, normal men in a resting state will only tolerate the combined stress adequately for a short period of time.[1] Any increase in the thermal stress or in other forms of cardiovascular stress such as exertion may seriously jeopardize compensatory mechanisms controlling peripheral circulation. On the basis of these experimental findings, further studies are suggested to define the limits of tolerance for heat and tumbling, and cold and tumbling.

VII. PERFORMANCE STUDIES DURING TUMBLING

Performance studies and mission requirements

Although astronauts, military aviators, and airline pilots are commonly allocated to operational tasks on the basis of their proved performance in occupational tests, it is seldom possible to expose them to disorienting situations with any degree of safety. Accordingly, the allocation of men for particular missions is usually based on the comparison of one man against another and not on any objective test

[1] The tolerance to positive acceleration is also temperature dependent. For an account of this relationship see Burgess, B. F. Aerospace Med. 3[illegible]: 567–5[illegible], 195[illegible]

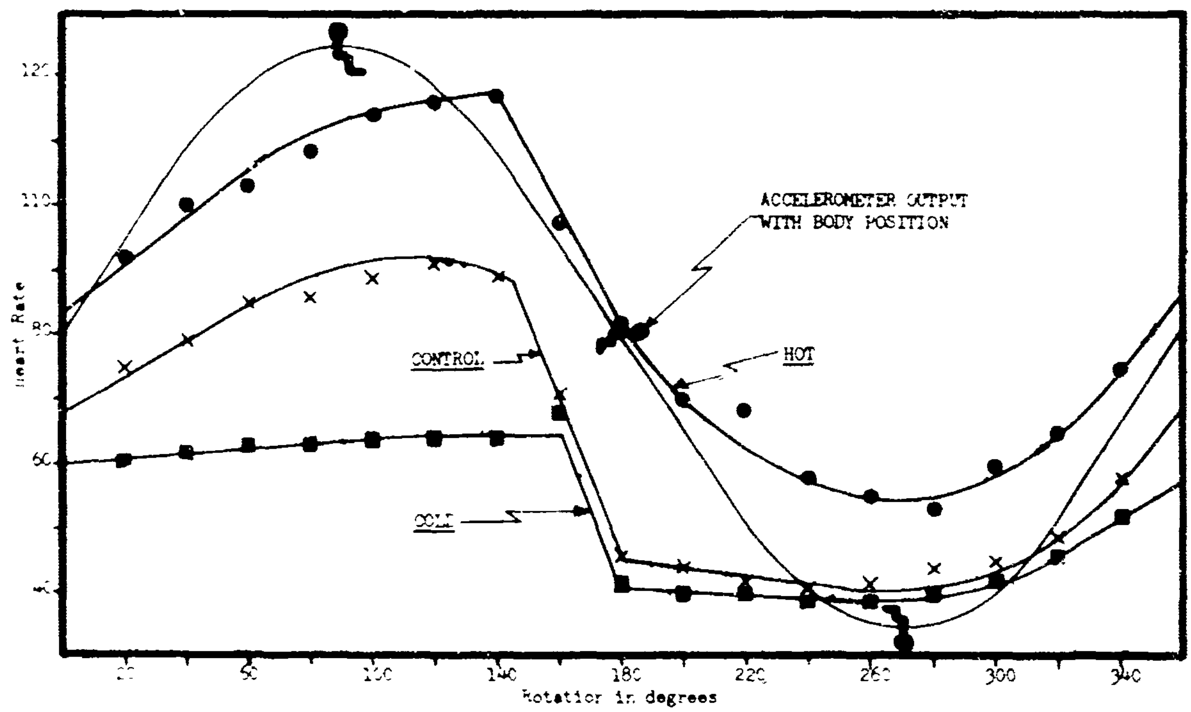


FIGURE 14

Effect of hot and cold ambient temperature on the response of the heart to rotation. Subject D.E., 25 Mar. 196- (hot), 11 Apr 196- (cold) pitch, 6 rpm.

administered immediately prior to a critical mission. Day-to-day changes in health status or well-being are sometimes the basis for the individual's seeking replacement if he feels that a mission may be prejudiced by the possibility of inferior performance. A real requirement exists for short-objective tests applied for day-to-day comparison and person-to-person comparison in teams of men standing by for critical operations.

In the absence of any standard method for assessing effects of tumbling on man or for predicting performance, two possibilities exist. First, it might be considered worthwhile to adapt one of the accepted tests or batteries of test methods used by experimental psychologists for assessing such items as wakefulness, agility, vigilance, and hand-eye coordination. Second, a specific simulator might be used to test the capability for handling controls under situations which resemble those likely to be experienced on mission work. Problems associated with the first approach include the difficulties in interpreting particular scores and in relating capability in tests to capability on operational tasks. The problem with the second approach is that simulators are usually built for a specific mission purpose and are restricted in their capability to tasks involved in that mission.

The absence of any satisfactory theory for performance buildup or decrement and for the effects of disorientation on performance suggests the need for a totally new approach to tumbling performance. Most aircraft and space vehicle personnel are commonly presented with commands by intercommunication system and with navigational information by visual displays. Because they have to manually operate or adjust controls, simple tasks involving hearing, vision, and manipulation with the

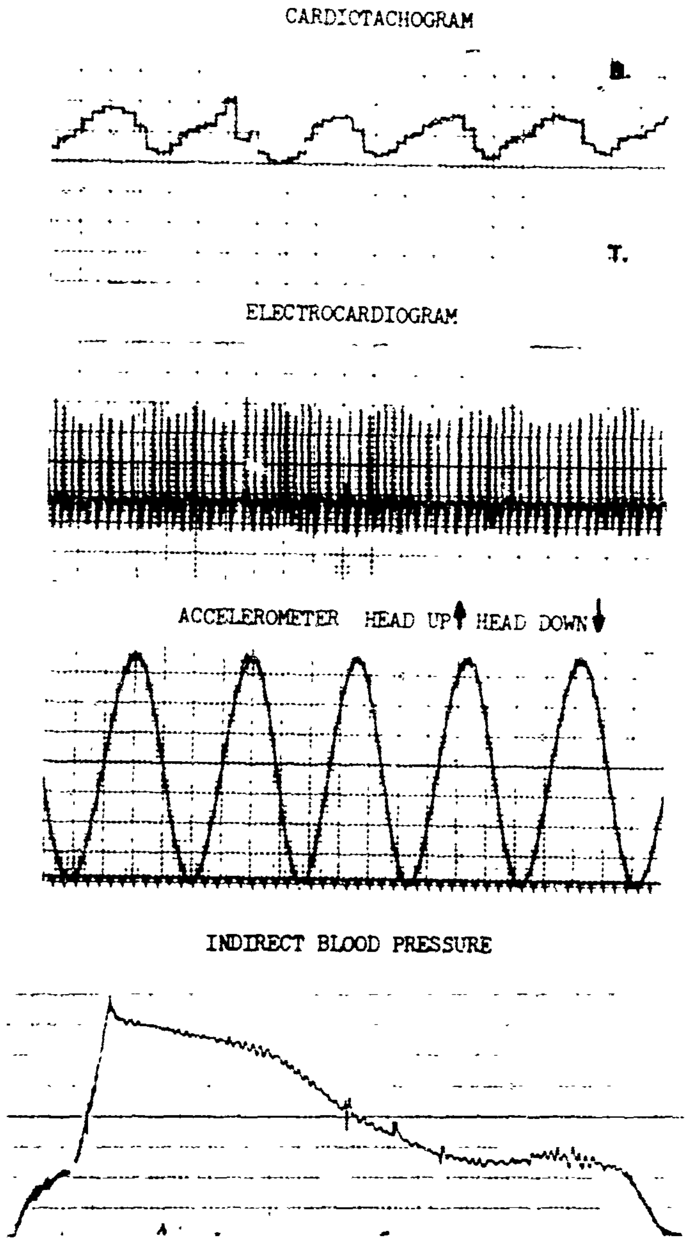


FIGURE 15A

Effects of high ambient temperatures during tumbling: Control run at 84° F. ambient temperature. Subject E.D.; 26 Mar 1968; pitch; 6 rpm.

hands might serve the dual purpose of (a) providing insight into deterioration of the special senses during disorientation, and (b) leading to a possible theory of performance decrement. Tests should be very brief and simple to master because many ARTS flights are short. A variety of experimental conditions was envisaged—for example, light or darkness, noise or quiet, acceleration or stationary. The chances of relating cause and effect under

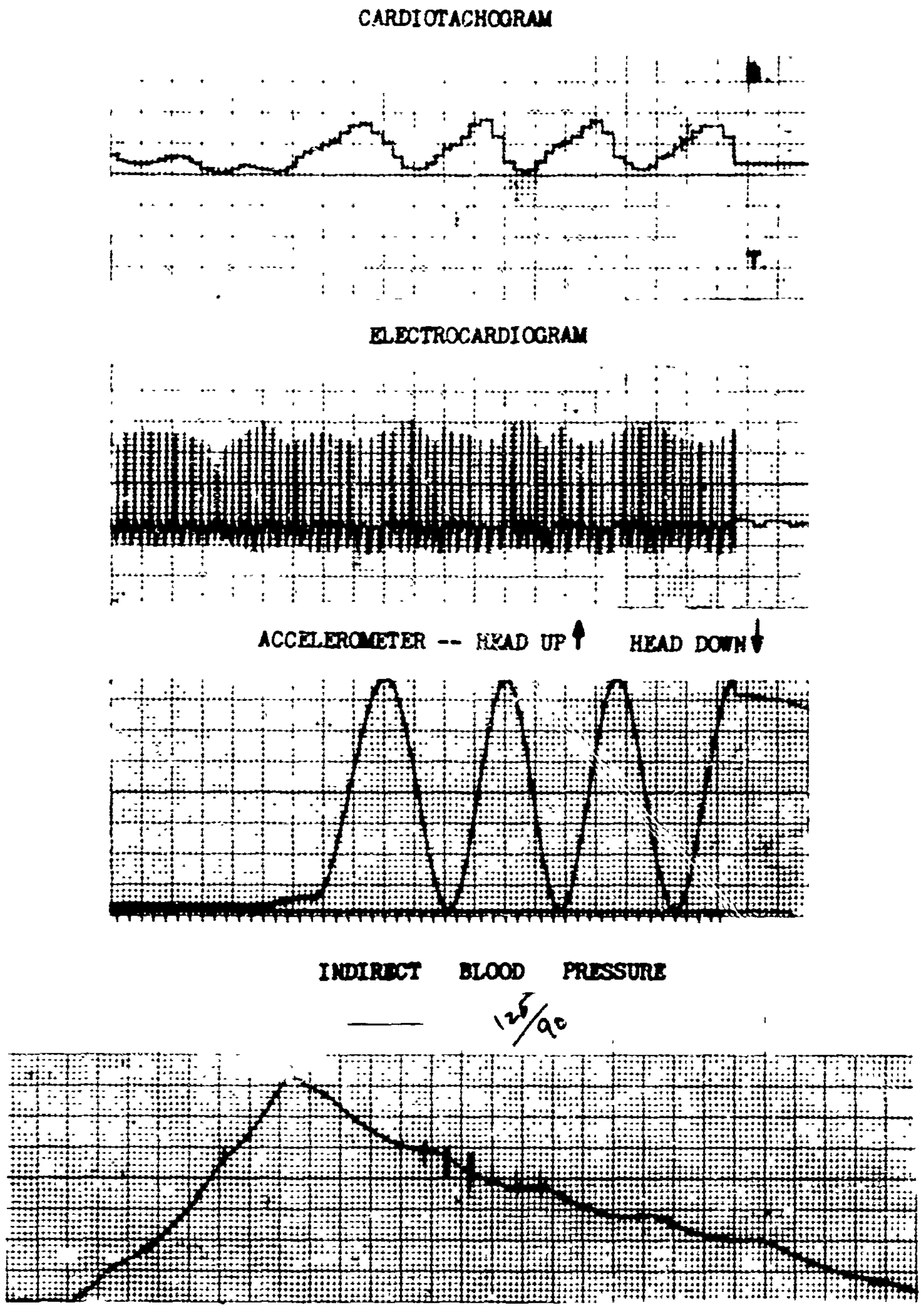


FIGURE 15B

Effects of high ambient temperatures during tumbling. Hot run at 102° F. ambient temperature. Subject and conditions same as in figure 15A.

such conditions seem much better with simple basic communication and response tasks than with those with more complex psychomotor testing procedures. The possibility that such tests would have to be applied under conditions of motion sickness was also kept in mind.

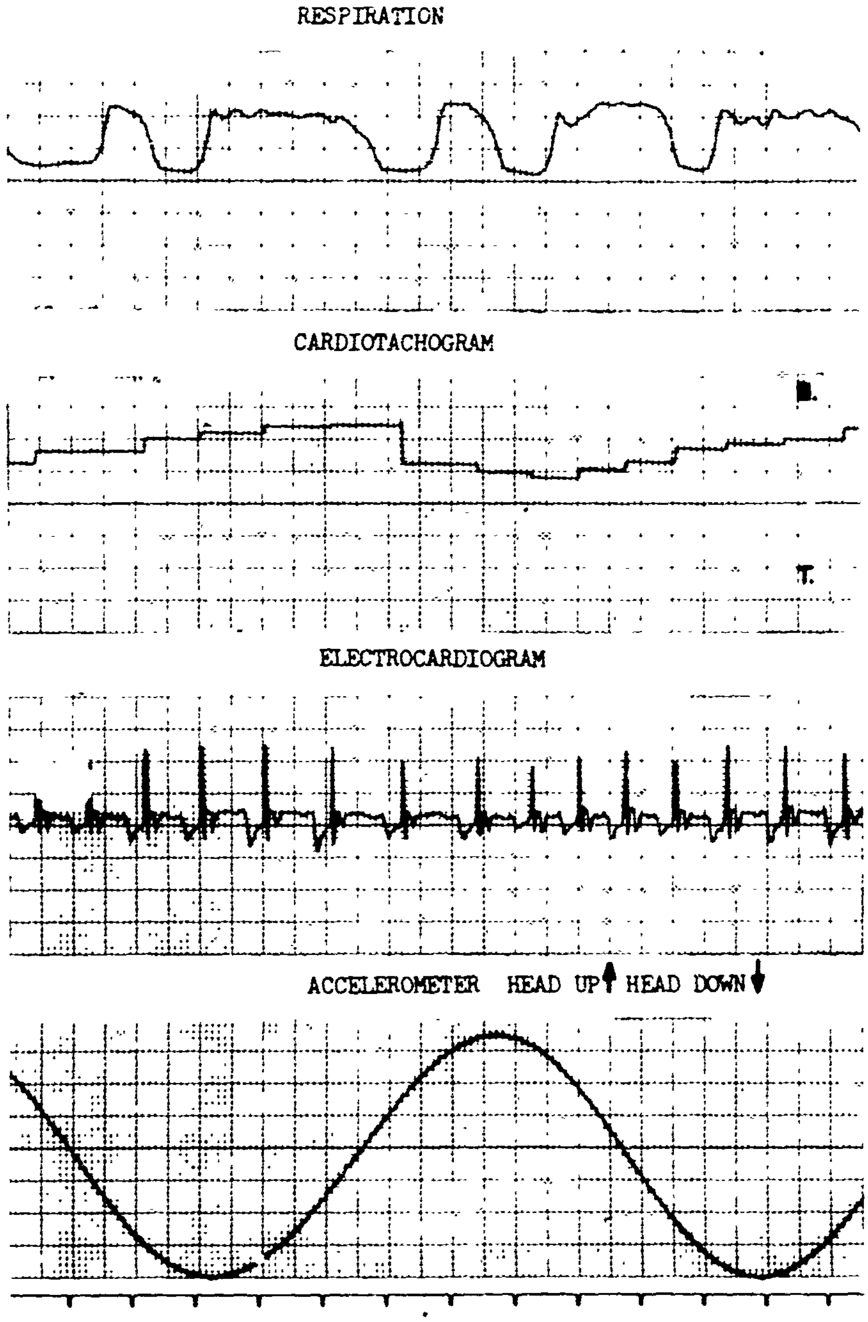


FIGURE 16A

Effects of low ambient temperatures during tumbling: Control run at 70° F. ambient temperature. Subject D.E.; 11 Apr. 1968; pitch; 6 rpm.

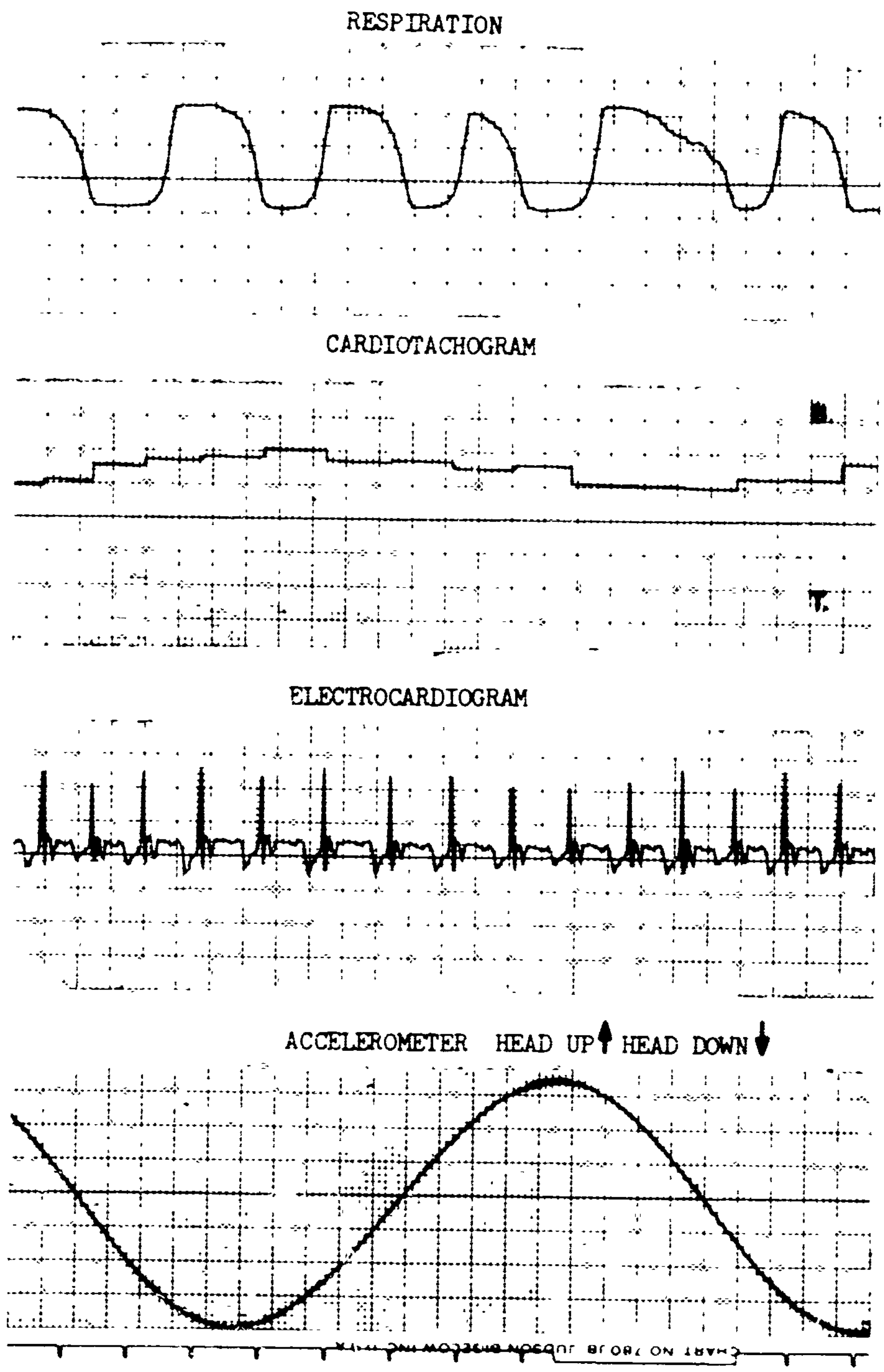


FIGURE 16B

Effects of low ambient temperatures during tumbling. Cold run at 57° F. ambient temperature. Subject and conditions same as in figure 16A.

Quantitation of performance

Four closely similar tasks were devised for use in the ARTS. Each involved the use of the intercommunication system, the imposition of a standard task, and stop-watch timing of segments of the overall program. A summary of test conditions and results is given in table V. Packs of simple flashcards were procured and arranged in subpacks of 10. On each card were two single digits between 0 and 9 with a + or − sign to indicate addition or subtraction. The purpose of each segment of the test was to run quickly through 10 cards and report directly the sums or differences to the observer, whose responsibility it was to measure the time taken. Information was presented to the subjects in one of four ways:

A mode (auditory): Intercommunication system.

V mode (visual): A remote figure display system in the field of vision of the subject and remotely controlled by him to move quickly from one operation to the next.

M mode (manipulating): A display involving manipulation and reading of cards held in the hands of the subjects.

F mode (flying): The same hand-held display used with instructions for the subject to look up between every addition or subtraction and focus his gaze on a point representing a distant object such as might be seen through the forward window of an aircraft.

TABLE V

Performance experiments

Number of subjects:	17
Number of test runs:	78
Modes tested:	Pitch
	Pitch forward
	Roll
	Yaw
	Pitch + roll
	Roll + yaw
	Pitch + yaw
	Pitch + roll + yaw
	Random
Range:	3-24 rpm
Typical results:	A 21% performance decrement in 4 men exposed to 6-rpm rotation in random axis while performing visual, auditory, and manipulating tasks.

One of the main causes of disorientation experienced by the pilots of high-performance aircraft is the need to alternate between visual and instrument flight rules when operating in scattered clouds. The four tasks, each occupying 15 to 25 seconds for 10 cards, were applied repeatedly at 0 rpm in order to establish a training curve and reach a steady state. They were later applied in precisely the same fashion in representative patterns of low-, moderate-, and high-speed rotation in various axes. The plan called for subjective sensations to be reported to the observer at will by the subject and for questions to be asked by the monitor as to perception of motion or stillness, vertical position, and the like.

Table VI outlines those experiments on performance which were successfully completed without onset of disorientation or motion sickness and those in which either disorientation or motion sickness, or both, were encountered. Results in the former case were evaluated in terms of the time taken to complete the series of digital manipulations in four modes. Findings on 4 subjects showed that a task which required 20 seconds when applied at 0 rpm in the ARTS required 2.5 to 4.3 seconds longer when rotating at 3 rpm. Ranking orders for the eight axes of rotation, the four modes of presentation, and the 4 subjects are given in table VII. Random rotation caused the test to take considerably longer than all other types of rotation. The auditory mode proved to take longer than the other three modes of data presentation.

In another series, 960 operations by subject E.O. were carried out in similar fashion in eight axes of rotation using the same four modes of presentation. Tests were run at 3, 6, and 12 rpm in order to estimate the effects of rotational velocity. Although the results are for 1 man only and could not therefore be fully balanced in the statistical sense, they showed consistently that this subject preferred random axis rotation, and that rotation in pure roll caused the normal 20-second task to require

TABLE VI

Performance studies during tumbling

Completed tests	Tests incomplete due to disorientation, motion sickness, or other cause*
A. Subjects: F.H., S.K., J S, D Z. Rotations: Roll Pitch Yaw Random Roll + pitch Roll + yaw Pitch + yaw Roll + pitch + yaw (Order changed for each subject) 3 rpm Modes: Auditory Visual Manipulating "Flying" 1,440 operations; 36 test runs	C. Subjects reporting disorientation prior to test completion: J F, N.C., E D., G.C., E O, D S. Rotations: Pitch Roll Yaw Random Pitch + roll Roll + yaw Pitch + roll + yaw Spit 3 to 30 rpm 23 test runs
B. Subject E.O. Rotations: Roll Pitch Yaw Random Roll + pitch Roll + yaw Pitch + yaw Roll + pitch + yaw 3 rpm in each: 3, 6, 12 Modes: Auditory Visual Manipulating "Flying" 960 operations; 8 test runs	D. Subjects reporting motion sickness prior to test completion: J.F., E.D., F.H., D.S., S.K., N.C., E.O. Rotations: Pitch Roll Yaw Pitch + yaw Yaw + roll Pitch + roll + yaw Spit 3 to 30 rpm 31 test runs

*In the final analysis, subjects reporting disorientation or motion sickness in other series of experiments were considered in combination with *C* and *D*

5 seconds longer for completion. In this subject the unaccustomed rotation in yaw also presented difficulty and the standard tasks took an average of 3.75 seconds longer to complete in pure yaw and 2.25 seconds longer in pitch plus yaw. Among other instances of personal difference for this subject was the difficulty experienced accepting data by the "F" (flying) mode of presentation. The standard task took 3.4 seconds longer than optimum when presented in the "F" mode, but only 1.6 seconds longer in the "A" mode. It was concluded that subject E.O. worked better with audio communication and had no difficulty with hearing, as was observed in 2 of the 4 subjects in the previous group. A final important finding for subject E.O. was that speed of rotation had little effect at this range of

TABLE VII

Performance decrements in four simple numeric processing tasks

Rank order for four tasks at 3 rpm (pitch)

1. Auditory input
2. Simulated visual flying task.
3. Visual input
4. Simulated manipulation flying task.

Notes:

Largest increase in time taken (auditory): 3.9 sec.

Smallest increase in time taken (manipulation): 2.5 sec

Optimum time for test (0 rpm): 20.6 sec.

Change: 12% to 19%

Rank order of eight rotational modes at 3 rpm (all tasks)

1. Random
2. Roll + yaw
3. Pitch
4. Roll + pitch
5. Yaw
6. Roll
7. Roll + pitch + yaw.
8. Pitch + yaw.

Notes:

Largest increase in time taken (random): 4.3 sec.

Smallest increase in time taken (pitch and yaw): 2 6 sec

Optimum time for test (0 rpm): 20.6 sec.

Change: 12% to 21%

rpm's. Thus, the increment for 12 rpm was +2 seconds or 10%, whereas at 3 rpm it was 2.6 seconds or 13%—both considerably smaller than the effects when axis of rotation and mode of presentation were changed. An extra experiment was therefore carried out with the subject in the yaw axis, during which he was asked to perform the same tests at 0, 6, 12, 18, 24, and 30 rpm. The subject found it difficult to concentrate at 24 rpm and impossible to continue the test at 30 rpm.

Disorientation and motion sickness

In the rest of the experiments subjective sensations of disorientation, observer-noted signs of disorientation, and subjective sensations of sickness were listed in an analysis using a logarithmic scale reported recently by Graybiel and his colleagues (21). Six subjects reported *disorientation* in 23 test runs carried out at 3 to 30 rpm in eight modes of rotation, including spit. Seven subjects reported symptoms of *motion sickness* in 31 test runs carried out at 3 to 30 rpm in seven modes of rotation, including spit. These data were combined with observations in other series of experiments to produce the severity ratings for all subjects. Symptoms considered in scoring motion sickness are given in table VIII. A scoring system designed along similar lines was applied to ranking of disorientation (table IX). Subject-to-subject differences for disorientation and motion sickness are given in table X. Table XI shows how the point scores are added in order to assess the level of severity under the terms slight, moderate, severe, or frank. Table XII is a complete analysis of the symptoms of motion sickness observed, ranging from flushing and headache through marked nausea and retching. There was no frank vomiting. Disorientation ranged from sensations of slight dizziness and difficulty in judging motion through inability to tolerate further motion (table XIII).

When the scores for disorientation and motion sickness are plotted on the same dimensional axes (figs. 17A and 17B), it is seen that: (a) disorientation occurred with equally high frequency in pitch, roll, and pitch plus roll, and there was also disorientation in yaw and random axis rotation; (b) motion sickness occurred primarily in pitch rotation and only to a minor extent in other axes of rotation; and (c) slight symptoms were seen with far greater frequency in disorientation than in motion sickness.

These observations confirm observer reports that rotation patterns which produce strong disorientation do not necessarily produce motion sickness, and vice versa. They suggest that the mechanisms that cause motion sickness differ from those which cause disorientation.

TABLE VIII

*Symptoms considered in scoring motion sickness**

Symptom	Suggested score (points)
Epigastric awareness	1
Flushing	1
Headache	1
Dizziness—eyes closed	1
Dizziness—eyes open	1
Epigastric discomfort	2
Slight pallor	2
Cold sweating (slight)	2
Slightly increased salivation	2
Slight drowsiness	2
Nausea (slight)	4
Moderate pallor	4
Cold sweating (moderate)	4
Moderately increased salivation	4
Moderate drowsiness	4
Moderate to marked nausea	8
Marked pallor	8
Cold sweating (severe)	8
Markedly increased salivation	8
Marked drowsiness	8
Vomiting	16
Retching	16

*Modified from Graybiel et al (21)

TABLE IX

Symptoms considered in disorientation

Symptom	Suggested score (points)
Dizziness—eyes closed	1
Dizziness—eyes open	1
Headache	1
Simple misjudgments of motion vectors	1
Delay in perceiving start or stop	1
Slight drowsiness	2
Difficulty in visual fixation	2
Perceptible spatial disorientation	2
Perceptible aftereffects of changed motion	2
Difficulty in perceiving vertical	2
Moderate drowsiness	4
Inability to distinguish whether stationary or moving	4
Illusions of motion; sensory inputs confused	4
Bizarre sensations of movement patterns	4
Occasional misjudgments in simple tasks	4
Marked drowsiness	8
Motor tasks disturbed	8
Inability to perceive rotation, tumbling	8
Errors in mental tasks, 25%	8
Prolonged delay in executing movements and commands	8
Inability to tolerate further motion	16
Inability to continue sensorimotor tasks	16
Inability to stand or walk	16

TABLE X

Subject groupings by sensitivity or resistance to disorientation and motion sickness

Present disorientation		Present motion sickness	
Sensitive			
G.H.*	J.F.	T.S.	E.D.
G.C.*	E.O.	E.O.	R.K.
J.L.	N.C.	D.E.	S.K.
D.S.	W.R.	D.S.	D.B.
S.L.	E.D.	J.F.	V.K.
J.N.*		N.C.	R.P.
		F.H.	J.T.
Resistant			
V.K.	T.S.	D.W.	J.S.
L.M.	D.W.	L.M.	G.H.*
B.W.	F.H.	B.W.	J.L.
S.H.	D.E.	S.H.	S.L.
D.Z.	R.K.	D.Z.	J.N.*
P.P.	S.K.	P.P.	W.R.
E.M.	D.B.	E.M.	G.C.*
M.D.	R.P.	M.D.	
J.S.	J.T.		

Groupings are based on reported severity of symptoms and corrected for number of runs.

*Subjects regarded as extremely insensitive to sickness, yet capable of recognizing disorientation and adapting to it. They would be recommended for training prior to critical space or flying operations.

TABLE XI

Classification and scoring of disorientation and motion sickness

Level of severity	Points	Abbreviation	
Slight	1-2	SI	DI
Moderate	3-4	SIIA	DIIA
Moderate	5-7	SIIB	DIIB
Severe	8-15	SIII	DIII
Frank sickness or disorientation	16	SIV	DIV
	Note 1	Note 2	Note 3

Note 1—Numeric scores used to sum the severity of effects and to compare the sensitivity, tolerance, or insensitivity of individual subjects

Note 2—Modified from Graybiel et al (21).

Note 3—Based on the analogous scoring described in table IX.

Significance for mission planning

Perhaps the most important conclusion from the above experiments is that subject-to-subject performance differences exist for specific reasons. For example, one man was unable to handle incoming information by auditory means, while another had particular difficulty with the "F" mode. If properly used, tests of this sort might be administered to available candidates for a particular mission and preliminary selection based on the highest performance in a desired or critical operational mode. A candidate who did not score well in some essential task or maneuver might then

TABLE XII

Reported motion sickness and its causation

Category	Subject and date	Symptom	Rate (rpm)	Mode of rotation	Total score	Total cases
Score 1	T.S. [illegible]967	Headache	6	Pitch	1	2
	[illegible].K. [illegible] Apr. 1968	Flushing	6	Pitch	1	
					— 2	
Score 2	T.S. 22 Nov. 1967	Slight cold sweating	6	Pitch	2	
	N.C. 11 Jan. 1968	Stomach discomfort	18	Roll + yaw + pitch	2	
	N.C. 11 Jan. 1968	Stomach discomfort	9	Pitch	2	7
	S.K. 28 Feb. 1968	Stomach discomfort	12	Yaw	2	
	S.K. 28 Feb. 1968	Slight cold sweating	12	Yaw	2	
	J.F. 19 Feb. 1968	Slight cold sweating	30	Spit	2	
	N.C. 6 Mar. 1968	Slight cold sweating	12	Pitch	2	
					— 14	
Score 4	D.E. 21 Mar. 1967	Slight nausea	12	Pitch	4	
	J.F. 5 Jan. 1968	Slight nausea	12	Yaw + roll	4	
	N.C. 11 Jan. 1968	Slight nausea	18	Roll + yaw + pitch	4	
	F.H. 16 Jan. 1968	Slight nausea	12	Pitch	4	8
	D.S. 17 Jan. 1968	Slight nausea	3	Roll	4	
	S.K. 28 Feb. 1968	Slight nausea	12	Pitch + y[illegible]w	4	
	E.O. 7 Mar. 1968	Slight nausea	12	Pitch + yaw	4	
	V.K. 9 [illegible]pr. 1968	Slight nausea	6	Pitch	4	
					— 32	

TABLE XII (contd.)

Category	Subject and date	Symptom	Rate (rpm)	Mode of rotation	Total score	Total cases
Score 8	F.H. 16 Jan. 1968	Marked nausea	6	Pitch	8	
	S.K. 28 Feb. 1968	Marked nausea	12	Pitch	8	4
	R.K. 15 Apr. 1968	Marked nausea	6	Pitch	8	
	J.T 17 Apr. 1968	Marked nausea	6	Pitch	8	
					32	
Score 16	E.D. 11 Jan. 1968	Retching	12	Roll	16	
	R.P. 15 Apr. 1968	Retching	6	Pitch	16	3
	D.B. 24 Apr. 1968	Retching	6	Pitch	16	
					48	24

work for improvement along specific, well-directed lines on the task which gave him difficulty. A further possibility is that standard performances, as measured with specific tests, be required for all men allocated to a particular mission involving tumbling or similar risks.

There is no doubt that considerable person-to-person differences exist in such items as postural equilibrium. In a recent study of 1,000 aviators (13), considerable person-to-person differences were seen in nonvestibular and circulatory response. Benefits of training are apparent in such items as perception of the upright position (36). The use of training tasks and standard tests of perception of body position has been described in space operations by Graybiel et al. (20), while Guedry (24) has compared vestibular effects by applying standard tests in several rotating environments.

It is common knowledge that some persons are particularly sensitive to motion and are liable to become motion sick under conditions which do not affect others. Precise mechanisms for this kind of difference are not known, although the subject has been reviewed extensively by Tyler and Bard (49).

Our observed performance decrements, ranging up to 25% in magnitude, are of the same order of magnitude as shown by Useller and Algranti (51) in tests of pilots exposed to high-speed rotation. In the latter series 6% to 18% loss of performance occurred in performing complex tasks up to 70 rpm. It is perhaps new to record that performances at low rpm's (3 to 6 rpm) may be particularly disorienting and that random rotation, while causing a performance decrement, may not necessarily produce motion sickness as effectively as roll or pitch. A word of caution is required here because the nature and extent of subject-to-subject differences are not fully established. The quantitative effects described were obtained on 5 subjects. No difficulty is expected in extending this to a larger number, and it would seem desirable to apply standard tests at representative rotation and rpm's to a larger number of subjects in order to deter-

TABLE XIII

Reported disorientation and its causation

Category	Subject and date	Symptom	Rate (rpm)	Mode of rotation	Total score	Total cases
Score 1	E.D. 17 Jan. 1968	Slightly dizzy	3	Pitch	1	
	E.D. 17 Jan. 1968	Slightly dizzy	3	Pitch + roll	1	
	E.D. 17 Jan. 1968	Slightly dizzy	5	Roll + pitch + yaw	1	6
	G.C. 18 Jan. 1968	Delay (20-sec.) to report stop	3	Roll	1	
	D.S. 6 Mar. 1968	Early (15-sec.) report of stopping	—	Random	1	
	G.H. 7 Mar. 1968	Difficulty judging direction of motion	12	Pitch	1	
					6	
Score 2	J.F. 5 Jan. 1968	Slight drowsiness	6	Pitch + roll	2	
	E.O. 27 Feb. 1968	Difficulty in perceiving vertical	12	Roll	2	
	S.L. 31 Mar. 1967	Felt pitch backward at end of run	6	Pitch	2	
	D.S. 6 Mar. 1968	Reverse motion at end of run	18	Yaw	2	7
	J.F. 20 Mar. 1968	Reverse motion at end of run	30	Spit	2	
	J.N. 3 Apr. 1967	Turning to right at end of run	20	Pitch	2	
	J.L. 29 Apr. 1968	Rocking from side to side at end of run	6	Roll	2	
					14	
Score 4	S.L. 31 Mar. 1967	Rolling backwards	12	Pitch	4	
	J.F. 5 Jan. 1968	Manipulation problems	6	Yaw + roll	4	
	N.C. 11 Jan. 1968	Lying on back pitching from side to side	24	Roll	4	
	J.F. 19 Mar. 1968	Moving side to side	3	Spit	4	
	E.O. 27 Feb. 1968	On head most of time	12	Yaw	4	
	E.O. 27 Feb. 1968	On head most of time	—	Random	4	9

TABLE XIII (contd.)

Category	Subject and date	Symptom	Rate (rpm)	Mode of rotation	Total score	Total cases
	E.O. 27 Feb. 1968	On head most of time	12	Pitch + roll	4	
	N.C. 27 Feb. 1968	Flat on back	3	Pitch + roll	4	
	N.C. 27 Feb. 1968	Inability to distinguish stationary or motion	3	Pitch + roll	4	
					36	
Score 8	E.O. 27 Feb. 1968	Inability to perceive tumbling	12	Yaw	8	
	N.C. 27 Feb. 1968	Inability to perceive tumbling	12	Yaw	8	3
	N.C. 27 Feb. 1968	Inability to perceive tumbling	12	Random	8	
					24	
Score 16	W.R. 19 Mar. 1968	Inability to tolerate further motion	3	Roll	16	1
						26

mine: (a) whether even larger subject-to-subject differences may exist; and (b) whether training cannot effectively produce improvement in men exposed to repeated tumbling.

VIII. EXTENDED ROTATION

Long-term exposure, training, and adaptation

Early experiments on tumbling have shown that repeated exposure confers an increase in tolerance, as judged by the delayed onset of symptoms of nausea. Three interesting questions arise: (1) Is the reduced sensitivity on subsequent exposures due to physiologic adaptation analogous to heat acclimatization, or is it due to subject readiness to tolerate a known stress more willingly? (2) Is a man's increased tolerance dependent on the time of exposure to tumbling or upon the number of occasions on which he experiences it? (3) In cases of long exposure to tumbling, either experimentally or accidentally in space, does any evidence exist for a greater tolerance at the end of such exposure as compared to the beginning?

Procedure and findings

Six subjects were asked to submit to 6-rpm, pitch-forward tumbling for a period of 1 hour, or until the limit of tolerance was reached. Of the 6 subjects, 3 achieved 54 to 60 minutes, 1 achieved 22.5 minutes, and the remaining 2 achieved only 5 minutes. Three runs were aborted because of incipient nausea and faintness. Respiratory maneuvers including Valsalva and Mueller tests were applied during runs to test carotid sinus function during tumbling (31). It is interesting that those subjects who tolerated tumbling well had prior experience in the ARTS, whereas the subjects unable to tolerate the tumbling had no experience with the ARTS in two cases and only two runs in the third case. In those subjects who were able to tolerate long runs, there was a gradual decrease in the amplitude of the heart rate fluctuation caused by a lowering of the tachycardia without modification to the bradycardia level. It was not possible to determine when or how these changes occurred. Blood pressures at the start of the experiment were

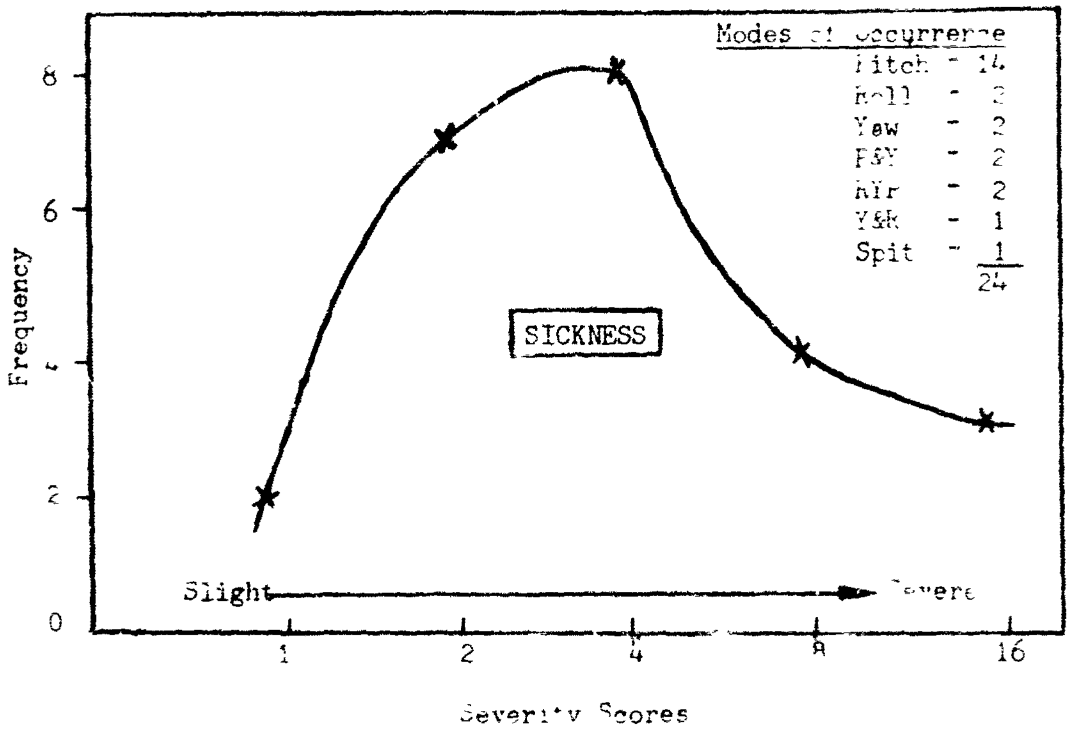


FIGURE 17A

Frequency versus severity of motion sickness

higher than those at the end of the run. In those subjects who did not tolerate runs well, the onset of this heart rate change appeared to be within a few minutes of the time at which they reported incipient nausea. Table XIV gives subjects, test runs, and modes tested for extended rotation experiments.

Typical records taken from the beginning and end of an extended rotation experiment are given in figures 18A and 18B. Figure 18A shows a record taken 2.5 minutes after commencement of tumbling. Heart rate ranged between 62 and 110 beats per minute, and systolic blood pressure was approximately 135 mm. Hg. After 57 minutes of tumbling (see figure 18B) the range of heart rate had decreased to 62 to 98 beats per minute, and systolic blood pressure was only 85 mm. Hg. This dramatic decrease in blood pressure occurred when the body was in the process of being tilted into the head-up position. Despite the very low blood pressure, no subjective sensations or faintness symptoms were reported; no doubt further rotation restored the normal blood pressure level before such effects developed.

Table XV shows the average heart rate for subject T.S., obtained from four measurements in a 2-year period from October 1966 to April 1968 during 6-rpm, pitch-forward tumbling. Measurements made before tumbling on each of the four occasions show a progressive downward trend in heart rate, and the same trend is seen in the average heart rates during tumbling. Within each experimental day there was a further downward trend, as seen in the data for the second, fourth, and sixth runs shown in columns 4 to 6.

Conclusions and interpretations

The heart rate findings in the above series are reminiscent of changes seen in the progressive adaptation to hard physical work in young men and of the reduced heart rate obtained in

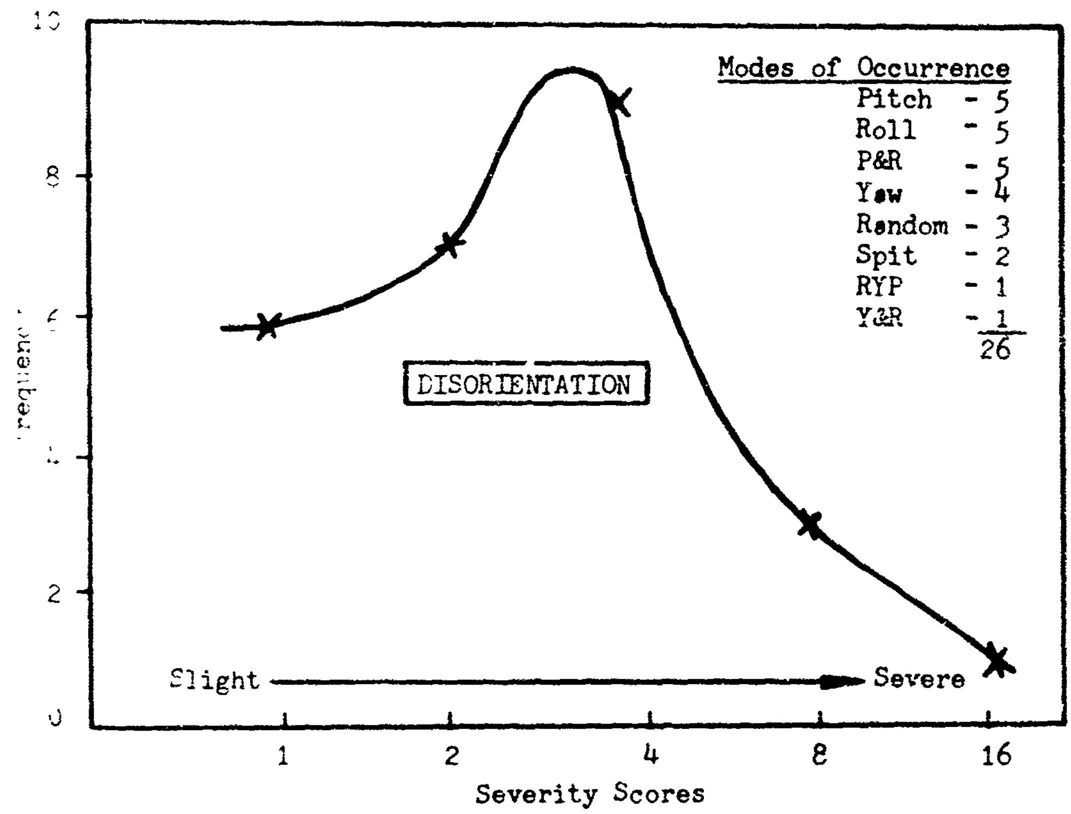


FIGURE 17B

Frequency versus severity of disorientation.

TABLE XIV

Experiments on extended rotation

Successful	Unsuccessful
Target time of 1 hour reached, 6 rpm, pitch forward.	Subjects terminated runs before 1 hour, 6 rpm, pitch forward.
N.C. 59 min. 50 sec.	R.P. 22 min. 27 sec.
F.H 58 min. 49 sec.	M.D. 5 min. 16 sec.
R.K. 54 min. 30 sec.	J.T. 5 min. 15 sec.
Prior experience of tumbling:	Prior experience of tumbling:
N.C. 21 runs	R.P. 2 runs
F.H. 17 runs	M.D. 0 runs
R.K. 2 runs	J.T. 0 runs
Incipient nausea terminated R.K.'s run.	Incipient nausea terminated run in two-thirds of the cases. (Faintness terminated M.D.'s run.)

response to a series of standard exposures to work in the heat. In both situations, adaptation of the cardiovascular system to stress is associated with peripheral vascular adaptations in the muscle and skin. The present findings show that subjects who are physically fit and have a past history of exposure to tumbling stress have also acquired physiologic means to compensate the cardiovascular embarrassment. The important consequence is that they tolerate the stress better. Exact mechanisms are not known. The study shows that tolerance can be acquired and suggests that a planned sequence of training runs on the ARTS might possibly increase resistance to other forms of dynamic stress.

The tendency of the heart rate to decrease in the prolonged run suggests that the circulatory response to the body's demand is being

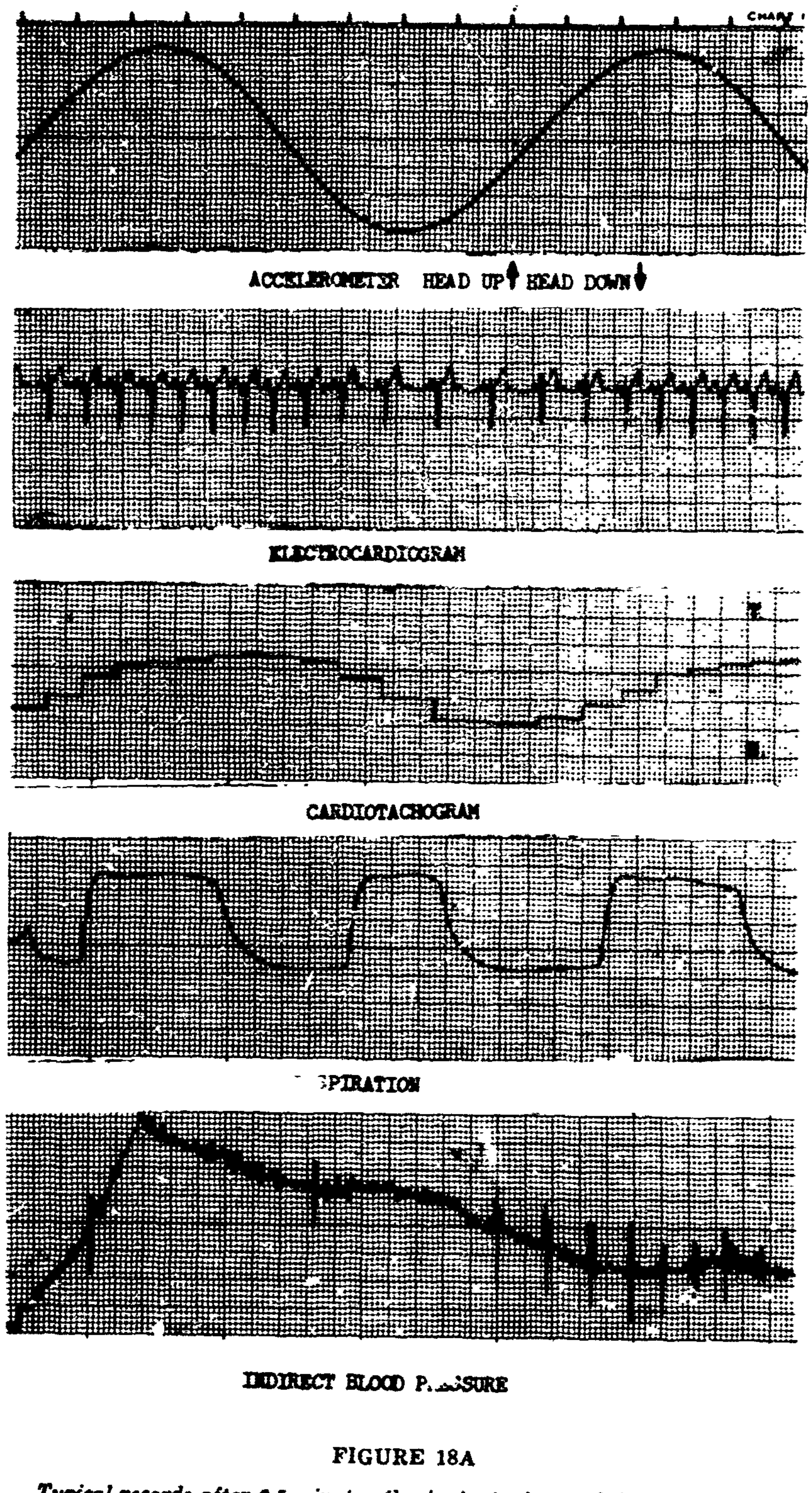


FIGURE 18A

Typical records after 2.5 minutes (beginning) of extended rotation. Subject N.C.; 2 Apr. 1968; pitch; 6 rpm.

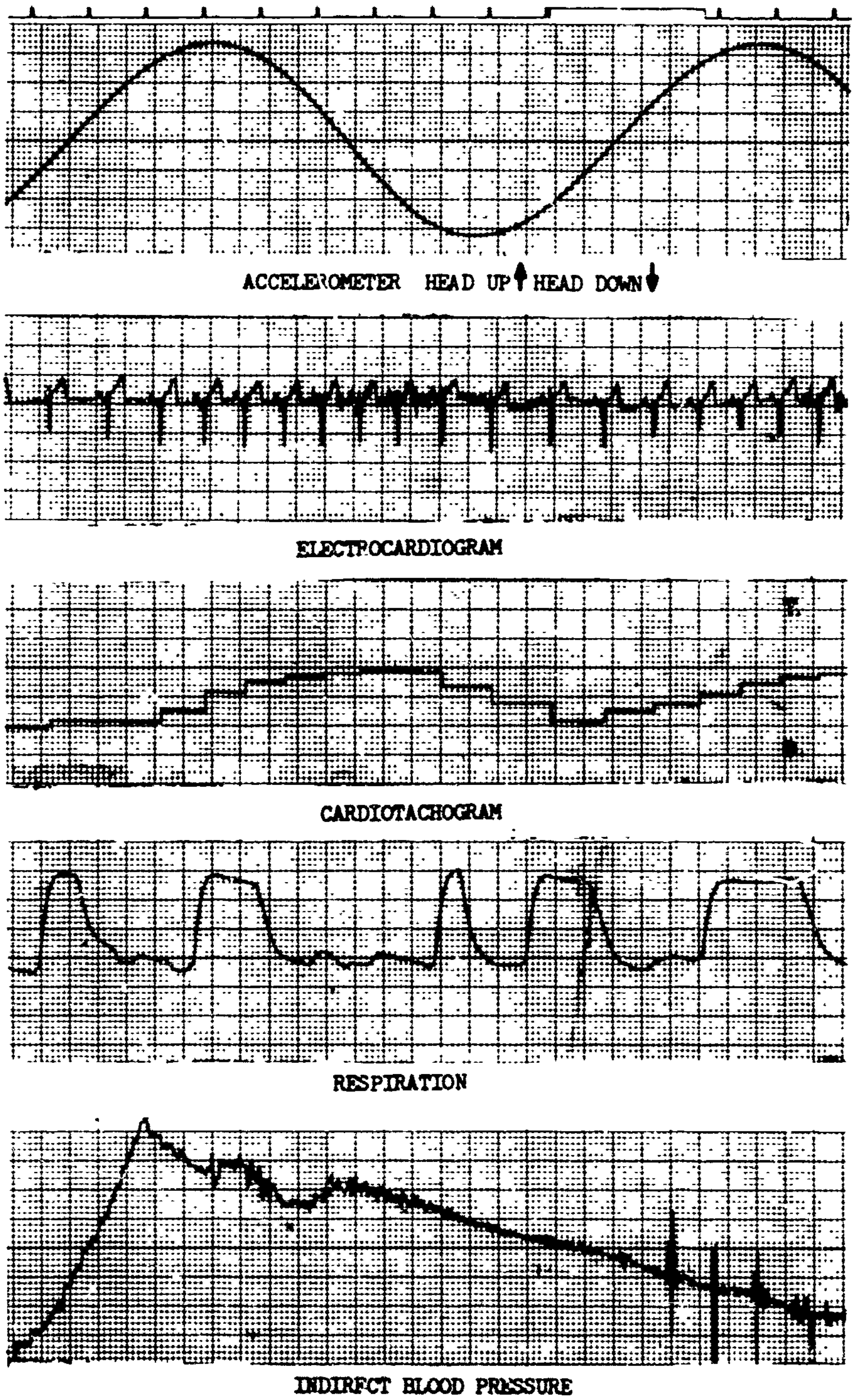


FIGURE 18B

Typical records after 57 minutes (end) of extended rotation. Subject and conditions same as in figure 18A.

TABLE XV

Tumbling heart rate response over a two-year experimental period

Average heart rate	Phase I	Phase II-A	Phase II-B				
	Oct. 1966	Mar. 1967 1st run	Nov. 1967			Apr. 1968	
			2d run	4th run	6th run	1st run	2d run
Before	80.2	69.3	64.7	51.7	43.5	55	54
During	69.1	70.7	64	58	49.3	60.3	55.3
After	69.5	67.3	63.3	59.2	48	57	50.2

Subject T.S., 6 rpm, pitch forward.

met by changes to stroke volume and cardiac output rather than by a simple rate increase. It may be that the initial response to the body's increased circulatory needs was an increase in the rate of cardiac pumping, but that there was a gradual shift to other more effective mechanisms with the passage of time. The ECG changes and the instability of blood pressure appear to be early indications of deterioration of the cardiovascular compensatory mechanism. Rotational stress applied from time to time induces or maintains a pathway for efficient cardiovascular compensation during tumbling.

Implications for men who are operationally exposed to biodynamic stress are considerable. The effects of long-duration exposure to gravitational stress have been studied by Frankenhaeuser (12) and by Graybiel and his colleagues (19), who exposed 4 men for 12 days in a room rotating at 10 rpm. Vestibular capability improves with practice in such moving situations (25), but it is common to see marked disorientation when an adapted man leaves a moving room in which he has been confined for a long period of time. Newson and Brady (34) also reported a prolonged run in a space station simulator; their study was carried out to explore the operational requirements for rotating space vehicles.

IX. DECONDITIONING BY WATER IMMERSION

Orthostatic deconditioning has recently been used as a means of simulating the effects of prolonged weightlessness in space. There is no question that water immersion to neck level for 6 hours produces orthostatic deconditioning (18, 41). Unless the level of immersion is tightly controlled, however, the transthoracic pressure difference may vary considerably from minute to minute and experiment to experiment. There is a high degree of variability in the methods described in the literature. Additional complications arise when the water temperature is either too hot or too cold. Further, if the skin becomes excessively h[illegible]ted by long immersion, there may be interfe[illegible]ce with normal peripheral blood flow.

A single case of water immersion was described by Graveline (18). The subject was enclosed in an impermeable suit, which highly restricted body movement, for 6 hours of continuous reclining. This deconditioning produced a dramatic change in tumbling heart rates. In particular, the tachycardia produced when moving from the head-down to the head-up position was extremely marked. This exciting observation suggested the need for future experiments on a larger number of subjects and the need for studying how quickly the deconditioning process can occur.

Methods and findings

Table XVI sets out the experimental procedure used in this extension of the work. Two series of experiments were carried out. In the first series 3 men were exposed to 6-rpm, pitch-forward tumbling for 3 to 5 minutes immediately before entering a large water tank. After

TABLE XVI

Experiments on deconditioning by water immersion

Subjects:	R.K., S.K., L.M., R.P., D.W.
Mode:	Pitch forward before and after orthostatic decon... ng by water immersion
Rate:	6 rpm
Number of test runs:	

Control	*Series I*	*Series II*	*Series III*	*Series IV*
All	1 hr. (D.W.)	2 hr. (L.M.)	4 hr. (S.K.)	6 hr. (all)
5	1	1	1	4

Typical analysis:

Respiration rates, systolic, diastolic, and pulse pressures, and resting heart rates all showed some evidence of orthostatic deconditioning. The dramatic tachycardia which was previously reported in a suited subject, confined in a restricted water bath, does not occur when subjects have skin-water contact and are free to move in a larger tank.

6 hours' immersion the experiment was repeated; in addition, each man left the tank for an interim test run some time during the 6-hour period. In one case the intermediate run was taken 1 hour after immersion; in the second case, after 2 hours; and in the third case, after 4 hours. In the second series, 2 men were inverted for a full 6-hour period with a control run before immersion and a test run on leaving the tank.

Water temperature was maintained in the comfort range between 89° and 93° F. The subjects either reclined on a horizontal board held approximately 18 inches below water level or moved into deeper water where they could stand upright with the water level at approximately neck height. Alternatively, there was room for one or two swimming strokes, and the men were allowed to move freely if they wished.

Results were dramatically different from the findings in the previously cited instance. Figures 19A and 19B show electrocardiograms, cardiotachograms, and respiratory waveforms before and after 2 hours' water immersion. ECG waveforms were identical, but the heart rate after 2 hours rose to 104 to 108 beats per minute when the subject entered the ARTS, as compared with a value of 65 to 72 beats per minute before immersion. Figure 20 shows tumbling effects on a subject before and after 4 hours of water immersion. No marked changes in ECG were noted. Bradycardia-tachycardia before immersion was 96 to 132 beats per minute, and this changed only slightly after immersion to 95 to 138 beats per minute. Table XVII shows the heart rate changes before tumbling, during tumbling, and after tumbling, before and after immersion. No regular changes in heart rate pattern were observed and no profound differences were noted. Table XVIII presents changes in blood pressure and respiratory rate in the 5 subjects before and after water immersion. Respiratory rates remained the same or increased. Both systolic and diastolic blood pressure changed during the run; the former became high and variable, while the latter became low and variable.

Interpretation and conclusion

The observations are taken to confirm that a degree of orthostatic deconditioning occurred under the experimental conditions. Peripheral circulatory impairment[2] took place and was

[2]No marked diuresis took place under the water temperature conditions used. It is therefore unlikely that massive plasma volume reduction occurred. Body weighings confirmed there was no large-scale loss in gross weight during immersion.

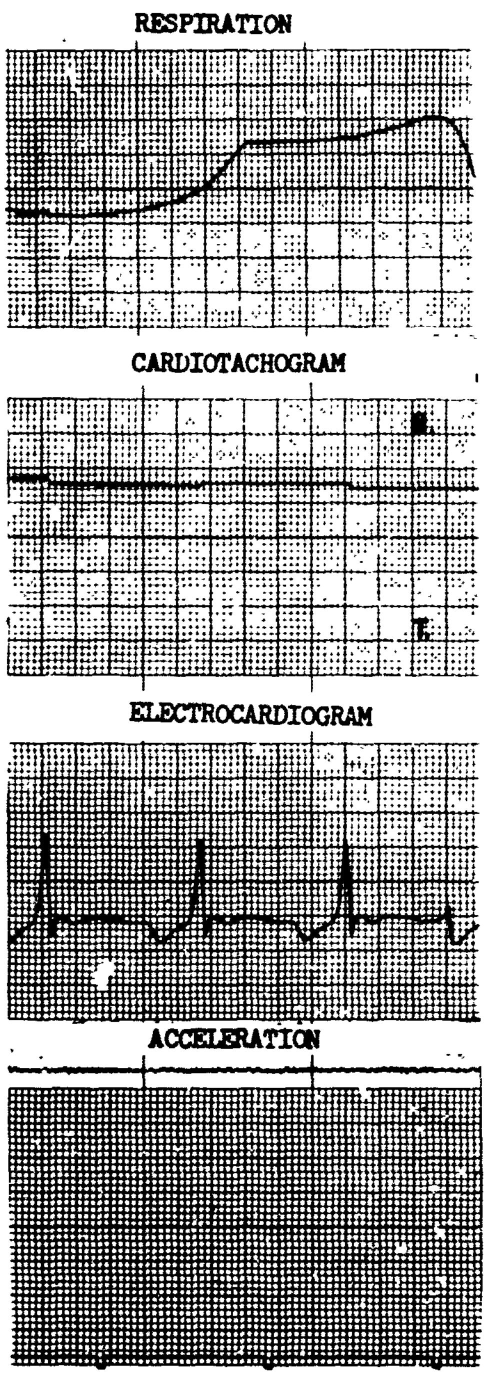


FIGURE 19A

Resting heart rates before 2 hours of water immersion. Subject L.M.; 3 Apr. 1968.

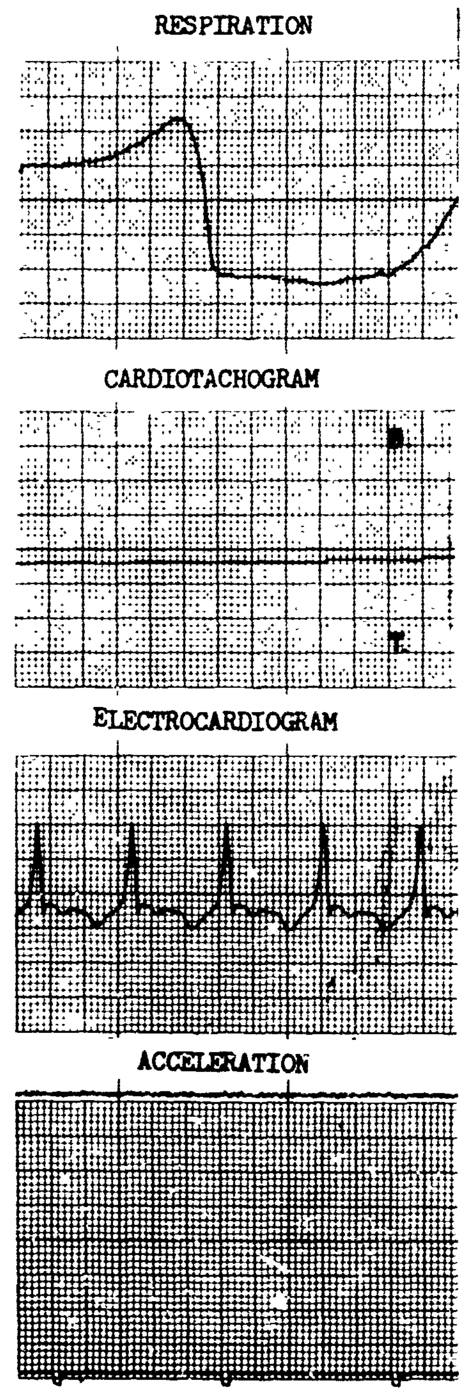


FIGURE 19B

Resting heart rates after 4 hours of water immersion, illustrating baseline shift of heart rate. Subject and date same as in figure 19A.

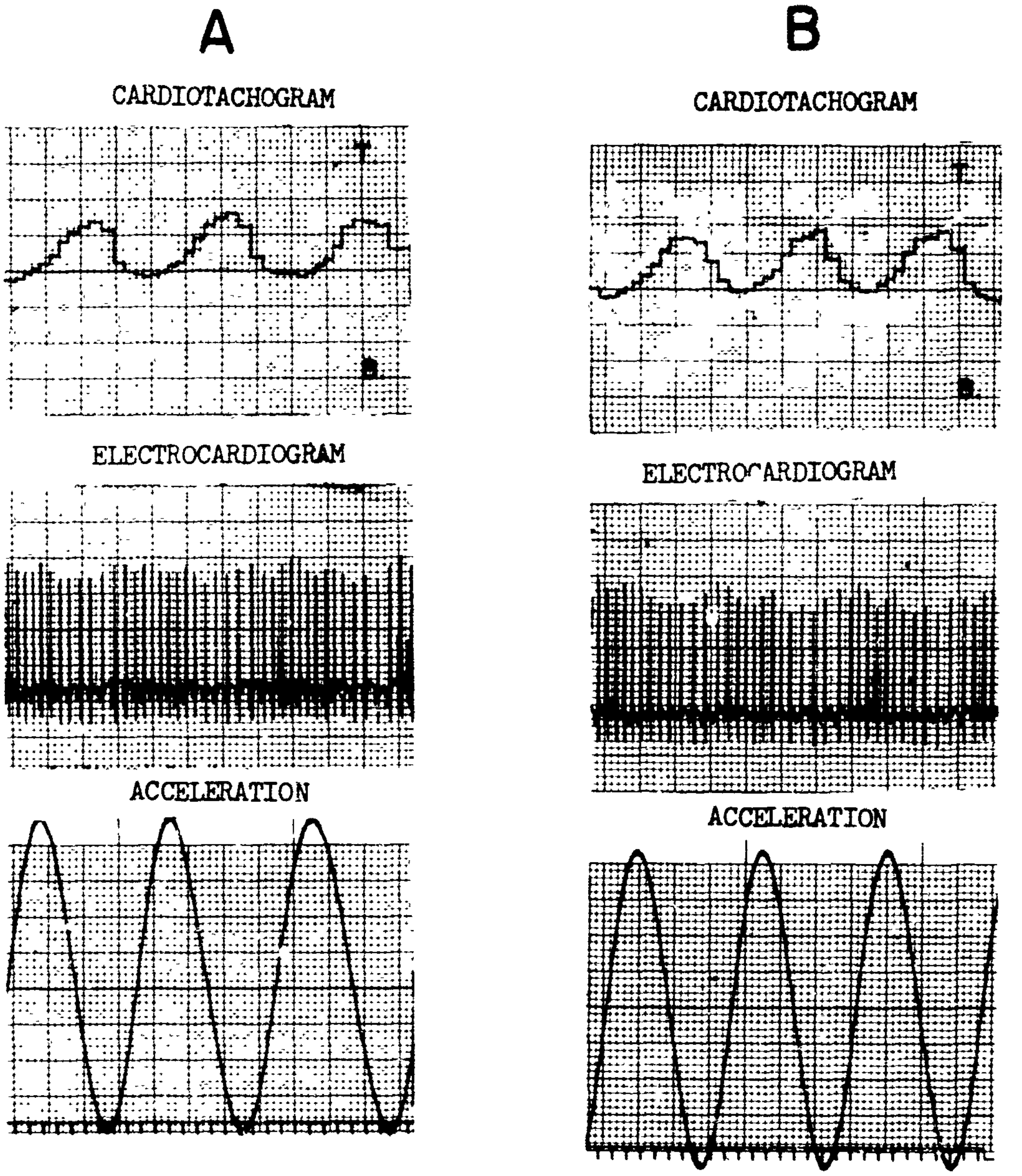


FIGURE 20

Effects of water immersion on tumbling responses. A. Tumbling before immersion. B. Tumbling after 4 hours' immersion. Subject S.K.; 3 Apr. 1968; pitch; 6 rpm.

indicated by the partial loss of cardiovascular stability when the men entered the ARTS for tumbling.

Of much more operational importance is the fact that potentially hazardous tachycardias did not take place.

Two important differences in experimental procedure help to explain this unexpected observation. In the first place, considerable skin hydration was observed on the 5 subjects in strong contrast to the excellent skin condition of the suited man in the previous pilot experiment. This might have caused emptying of

TABLE XVII

Heart rate changes in 5 subjects (unsuited) before and after water immersion

Subject and conditions	Heart rate					
	Bradycardia			Tachycardia		
	Before run	During run	After run	Before run	During run	After run
S.K.						
Baseline	79	65-68	83	104	97-100	103
After 4 hr. immersion	79	66-68	90	107	95-100	97
Test run II	83	62-67	86	97	88- 94	97
D.W.						
Baseline	75	61-62	77	88	97-100	92
Test run I	80	52-54	86	100	87- 87	97
Test run II	68	54-55	70	100	85- 88	86
L.M.						
Baseline	59	53-56	75	94	92-95	92
Test run I	83	53-55	86	107	97	107
R.K.						
Baseline	60	52-56	64	83	77-83	74
Test run II	68	53-58	63	103	81-88	94
R.P.						
Baseline	62	62	60	94	91-92	80
Test run II	75	59-61	68	115	89-91	97

blood from skin vessels to central circulation. The second difference was that prolonged water immersion in a horizontal position amounts to bed rest in a supporting medium without the possibility of exercise and blood redistribution. In the present series the larger water tank did not require total rest and there was ample opportunity for blood redistribution to take place during postural changes and during occasional exercising movements. Thus, water immersion alone may not produce the tumbling impairment. A third difference (namely, the lack of effective control of transthoracic pressure difference) has already been noted; it is inherent if subjects are to be allowed freedom to move according to protocol.

Further experiments are needed to determine which, if any, of these factors so effectively produced tumbling deconditioning in the earlier trial. It is suggested that carefully controlled experiments be conducted including: (a) horizontal and vertical posture during immersion; (b) two or more levels of immersion; and (c) restraint versus freedom to move in the water.

An additional possibility is that tilt-table trials, with scoring of the response before and after immersion, be used as a means for measuring the deterioration due to immersion and developing a tumbling test with the ARTS. The former technic was recently used on sev-

TABLE XVIII

Blood pressure and respiration rate changes in 5 subjects (unsuited) before and after water immersion

Subject and conditions	Blood pressure, systolic			Blood pressure, diastolic			Respiration (breaths/min.)		
	Before run	During run	After run	Before run	During run	After run	Before run	During run	After run
S.K									
Baseline	115-120	140-145	110	75-80	65-75	90	16	26	24
After 4 hr. immersion	125-130	120-150	100-110	70-85	60-60	35-75	18	28	25
Test run II	115-120	—	115	80-80	—	85	24	29	23
D.W.									
Baseline	125-135	115	—	85-85	80	—	24	10	18
Test run I	115-120	—	125-125	35-85	—	80-95	21	—	20
Test run II	115-120	—	115-130	80-85	—	90-95	24	11	19
L.M.									
Baseline	145-150	135-165	135	85	65-70	75	20	22	22
Test run I	125	—	125-130	95-105	—	95	23	23	25
R.K.									
Baseline	105-120	—	110-125	85	—	80	10	13	11
Test run II	105	—	110	85	—	80	13	19	16
R.P.									
Baseline	120-125	100-140	135	80-85	55-75	85-80	23	11	16
Test run II	125	—	115-130	90-95	—	105-80	21	16	19

eral astronauts (3). The possibility exists that deconditioning and reconditioning experiments might be carried out on USAF or NASA candidates for space operations and that the candidates might indoctrinate themselves on the hazards of prolonged weightlessness by using the ARTS and the associated immersion facility.

X. ENGINEERING STATUS AND ARTS PERFORMANCE

Work carried out since completion of phase I (41) includes the following:

1. Relocation of the ARTS to a specially constructed area adjacent to other biodynamic equipment including the centrifuge and water immersion tank.

2. Construction and fitting of three new air bearings capable of supporting the weight of the loaded vehicle with reduced noise and higher rpm capability.

3. Construction and fitting of a remotely controlled equatorial drive, operative with fine discrimination at any angle of incidence.

4. Construction and fitting of a new polar drive underneath the ARTS, capable of operating the vehicle in pure yaw and of supplementing the equatorial drive when fast acceleration is required.

5. Design, fabrication, and installation of a completely new operating console, including communications equipment, in the new control room adjacent to the ARTS.

Successful trials with the new equipment have demonstrated vastly increased reliability and better performance of the ARTS.

Additional changes include the following:

1. Installation of a safety valve to prevent loss of air pressure in the event of compressor cut-out. The new valve allows the ARTS to be positioned correctly and the subjects evacuated in the eventuality of total power loss or pressure-line fracture.

2. Fitting of safety alarms to alert operating personnel to a subject requirement or loss of operating air pressure.

3. Fitting of a new and highly effective intercommunication system with speakers, allowing the operating team to work without earphones.

4. Installation of two new antennas to minimize signal loss during certain critical ARTS positions.

5. Labeling and marking the exterior surface of the ARTS to show axis rotation and subject position.

6. Improvements to the electrical storage battery installation and location of a canvas screen inside the subject cabin

7. Installation of a special circuit patch panel for rapid modifications in signal-processing circuitry.

8. Installation of new discriminator channels.

9. Installation inside the subject cabin of a special digital counting device for performance testing.

The combined effect of these improvements is such as to permit up to 8 experiments to be carried out within a single day. Utilization factors of the ARTS are vastly superior to their original values.

Figure 21 shows the sitting position of the subject and his geometrical relationship to the ARTS, including its equator, south pole, and reference axes. It permits visualization of the position of the new external drive motors and demonstrates the initial reference position of the subject at the beginning of each experiment.

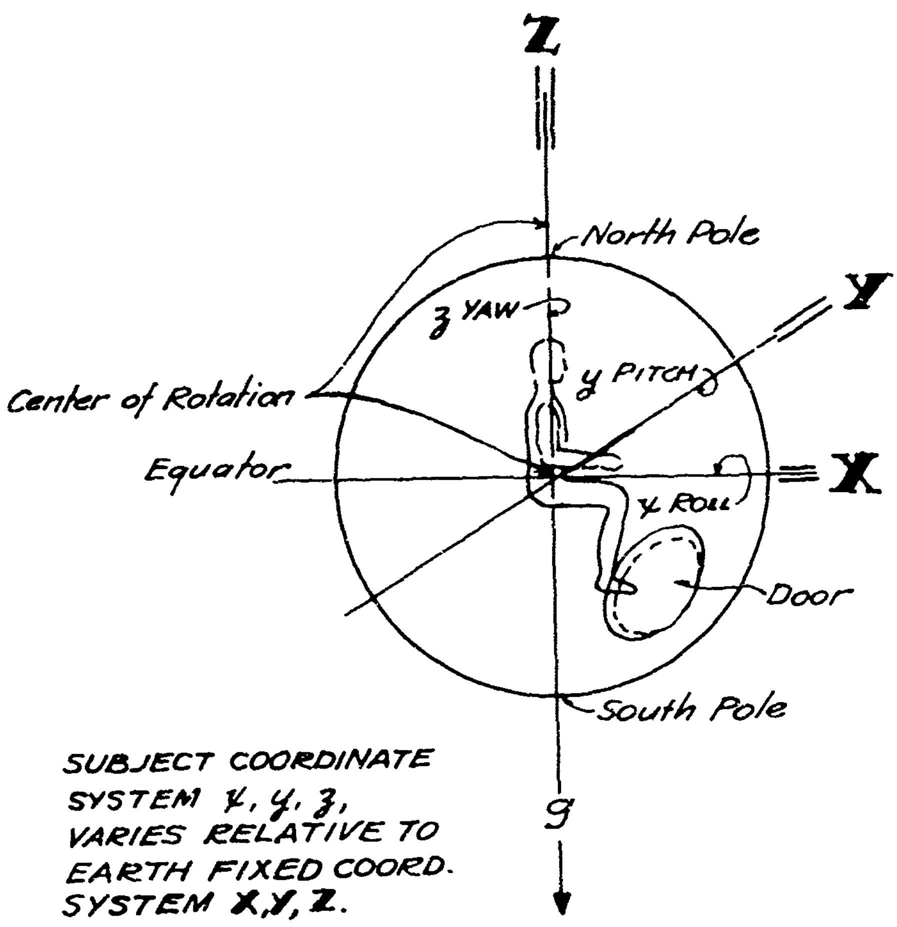


FIGURE 21
Initial reference position.

Figure 22 shows the arrangement of the new drive systems. Control is from the open console. Each system consists of two motors: (a) the larger motor drives a friction wheel which rides on the ARTS surface, accompanied by a trailing or directional wheel; (b) a smaller motor is used to change direction of the drive train. Also shown in the diagram are the positions of the three new air bearings and their relationship to the center of rotation of the ARTS and subject.

Performance tests and safety trials confirm that the ARTS now meets all performance specifications, including the capability to operate in all three axes of rotation. Available power is more than sufficient to achieve 60 rpm, as proved by unmanned trials. At the present time, the effective limit for random tumbling is about 40 rpm because most subjects rapidly become nauseated and cannot maintain flights at such high speeds. The maximum rpm for pure axis rotation is around 30 to 35 rpm, which is more than sufficient for all but maximum stress tests. Higher rpm's will undoubtedly be obtainable after careful balancing. The upper limit of tolerance for most subjects is about 25 rpm. A spectrum of tumbling and rotation speeds available with the ARTS is shown in table XIX. Further engineering details are given elsewhere (41).

XI. FUTURE WORK

A formal study of research and non-research possibilities in the future operation of the ARTS is recommended. The versatility of this vehicle and its capability for critical research studies can be regarded as well established, but require documentation. Its potential for use in personnel selection, training, and special indoctrination needs to be established and might well show unexpected and valuable uses.

It is recommended that such a study be related to (a) existing and future space programs including the USAF Manned Orbiting Laboratory program; (b) existing USAF missions (including support for operation and combat flying personnel by investigation of the disorientation hazard); (c) research targets (including greater understanding of the stress-strain relationships in man imposed by biodynamic stimulation).

Four specific steps are recommended: *Step 1* would be a study of the potential of the ARTS for training and selection of flying personnel and re-exposure of aircrew to motion stimuli after a period of layoff. *Step 2* would be a survey of the equipment necessary for installation within the ARTS to increase its training capability and to allow real-life situations to be simulated during tumbling and rotation. Of specific interest here is a U. S. Navy development involving overhead projection of real-life flying situations on movie film, together with biodynamic feedback of position change such as would actually be experienced in flying. A second possibility is the installation of devices for producing vibration, noise, and movement instability. These have importance as a means of simulating real-life events in aircraft and space vehicles; all three factors are known to cause serious disorientation in space vehicles and aircraft. *Step 3* would be detailed analysis and testing of selected motions not yet explored. Table XX lists a number of starting positions and ARTS movement patterns which are currently available. Many of these have not yet been investigated. Table XXI lists an additional series of tumbling and rotation modes which deserve study. Until such investigation is performed, the full potential of the vehicle will not be realized. *Step 4* involves further research use of the ARTS. Extensions of the present program might well be made to the areas of (a) respiratory events during tumbling; (b) direct blood pressure recording; (c) peripheral vascular investigations, including measurements of neurogenic response; and (d) further study of impedance methods for recording blood redistribution.

In summary, future uses of the ARTS should not be confined to basic physiologic research. There is a potential for applied research which deserves investigation, documentation, cost effectiveness studies, and discussion.

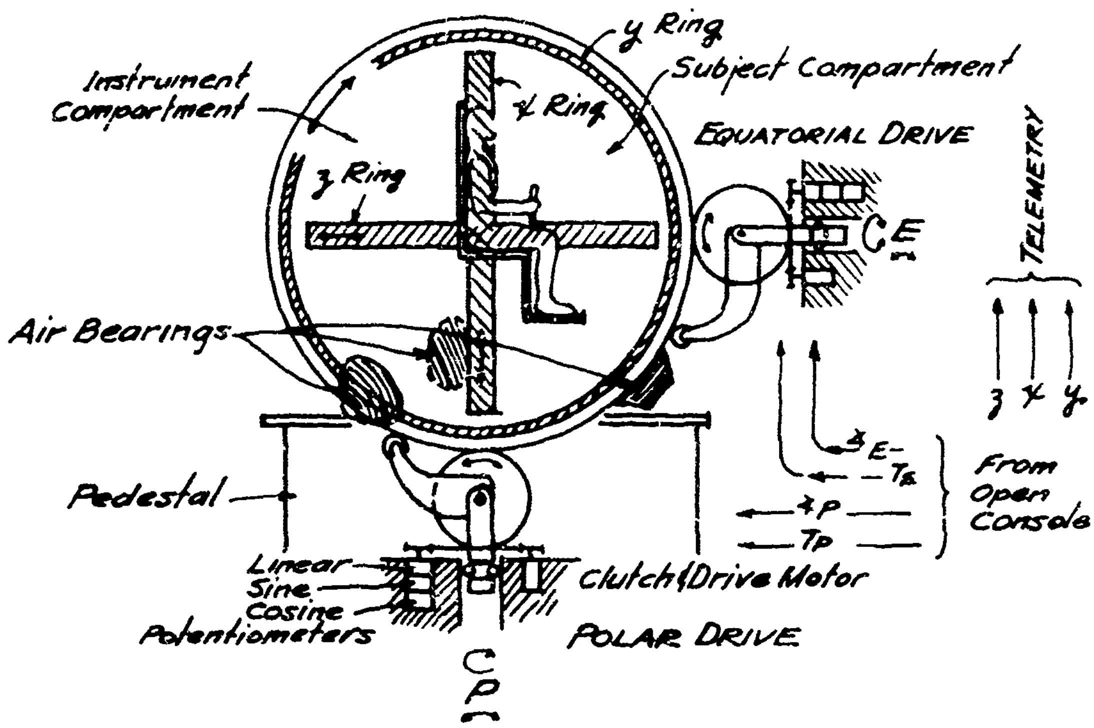


FIGURE 22

Arrangement of drive system.

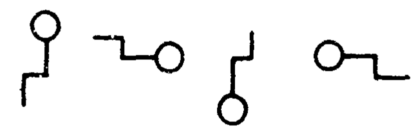
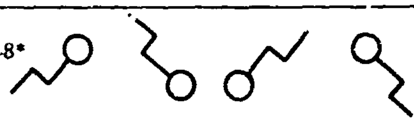
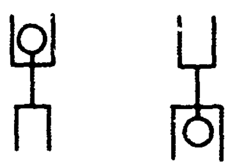
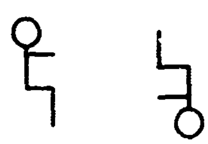
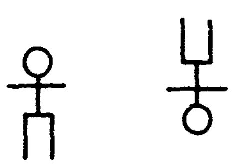
TABLE XIX

Spectrum of tumbling and rotation speeds available using ARTS

Dynamic performance	Rate (rpm)	Physiologic performance
Vehicle capability (unmanned) exceeds this level. →	60	
ARTS commences to gyroscope and moves progressively to rotation in its preferred dynamic pattern.	–	
	50	
	–	←Maximum manned flight maintainable for few seconds on'. because of vigorous vestibular and nauseating stimuli.
Effective limit for random tumbling. →	40	
Pure axis rotation still possible in selected axes—e.g., turntable position. →	–	←Minor oscillations and departures from pure axis rotation became disorienting and nauseating.
Maximum rpm for pure axis rotation. →	30	←Upper limit of tolerance for all but trained, resistant personnel.
	–	
	20	
Fastest manned rotation (phase I). →	–	
	10	←Upper limit of tolerance for sensitive subjects.
Runs for 3-min. at 6 rpm for routine screening tests. →	–	←Most subjects tolerate for 3 min. in any axis or in random rotation.

TABLE XX

Modes of tumbling and rotation currently available

Starting position (all sitting)	Vehicle pattern
1-4 	1-4 Roll, Pitch Yaw, Random
5-8* 	5-8 Roll and pitch Roll and yaw Pitch and yaw Roll and pitch and yaw
9-10* 	
11-12* 	9 Single revolutions 10 Quarter revolutions
13-14* 	11 Alternating fast-slow runs* (e.g., sinusoidal)
15-16* 	12 Intermittent runs* (e.g., square wave)

Left-hand column illustrates body posture at start of rotation. Right-hand column indicates mode of vehicle movement. Any combination of initial posture and vehicle movement can be produced at will.

*Not investigated so far.

TABLE XXI

Modes of tumbling and rotation for future consideration

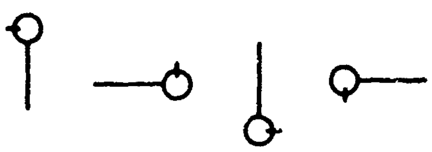
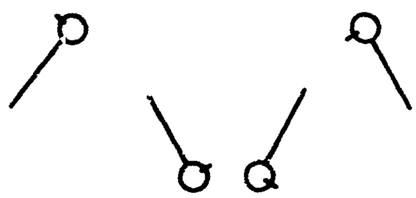
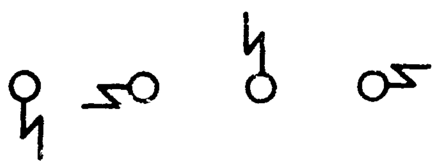
Starting position (lying/squatting, etc.)	Vehicle pattern
	Ultra slow rpm's
	Rotation with vibration added
	"Ladder" and "staircase" patterns
Associated positions with arms stretched	Subject controlled runs
Trunk fixation with head movements	Subject cancelling observer inputs
Off-center positions	Runs simulating aircraft maneuvers
Two-men riding positions	

TABLE XXII

Principal experimental topics and conclusions

Topic	Conclusions
Disorientation studies	Clear patterns of disorientation and of motion sickness were recorded during tumbling. Men who report disorientation do not necessarily become motion sick, or vice versa.
Effects of tumbling rate and axis	Acceleration to 30 rpm, pitch virtually abolished heart rate oscillations due to tumbling in 1 subject. The usual pattern returned immediately the vehicle was slowed.
Effects of heat and cold	Subjects tolerate combined stresses of tumbling and cold (55° to 58° F.) better than combined stresses of tumbling and heat (100° to 113° F.).
Thigh-cuff occlusions	Reduction of hydrostatic volume of blood does not greatly modify the dramatic pattern of tumbling bradycardia-tachycardia. Importance of blood redistribution and volume receptors is suggested.
Control capability and performance tests	Random rotation, reliance on auditory input, and tumbling at 3 to 6 rpm (or above 30 rpm) gave greatest difficulty to men doing performance tests.
Instrument checkout and demonstration runs	In 6 out of 45 experimental days, unexpected instrumentation and equipment difficulties prevented full test programing. Repairs, engineering development, part replacement, and preventive maintenance effectively remedied all difficulties.
Orthostatic deconditioning	Six-hour water immersion with skin-water contact and freedom to move in a large tank did not reproduce the effect (extreme deconditioning) previously observed in 1 immobile, suited subject.
Extended rotation	Three out of 4 men were able to tolerate continued tumbling (6 rpm, pitch forward) for 1 hour. Subjects develop increasing tolerance with repeated exposure.

TABLE XXIII

Summary of experiments performed

Experiments	Test runs	Subjects
Studies on disorientation	54	12
Effects of tumbling rate and axis	51	11
Effects of heat and cold	46	10
Thigh-cuff occlusion tests	45	8
Studies on control capability and performance tests	44	5
Instrument checkout and demonstration runs	24	10
Orthostatic deconditioning	12	5
Extended rotation	4	4
	280	29

XII. CONCLUSIONS

Table XXII lists the prime conclusions reached during phase II of research work on the ARTS. These conclusions range from the establishment of 25% performance decrements during certain kinds of tumbling to proof that redistributed blood volume plays a major part in the control of blood circulation. They affirm that weightlessness can be partially simulated by water immersion, and that there are significant person-to-person differences in tolerance to tumbling. Table XXIII summarizes the number of experiments performed.

It is suggested that ARTS performance characteristics are now sufficiently comprehensive to justify use of the facility for purposes other than research. The research field is not limited, but a unique facility now exists for several biodynamic purposes. Its future use may also range from ground-based training of the scientist-astronauts, who must biodynamically supplement their limited pilot experience before safe space missions can be undertaken, to applied research on combined stresses such as motion plus noise, inversion plus heat, and orthostatic conditioning plus muscular work.

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APPENDIX

A. Personal data on experimental subjects

B. Scheme of experiments

C. Test run schedule

D. Test runs and duration for individual subjects

E. Phase II subject register

A. Personal data on experimental subjects

Subject	Age (yr.)	Height (in.)	Weight (lb.)
Regular			
D.B.	24	68	150
W.B.	35	69	145
G.C.	20	70	175
N.C.	36	71	185
E.D.	33	65.5	165
M.D.	29	70	185
D.E.	31	70	159
F.H.	36	73	180
S.H.	35	71.5	185
R.K.	33	71.5	131
S.K.	34	71	175
V.K.	36	68	170
E.M.	39	68	160
L.M.	26	72	190
J.N.	31	71.5	194
E.O.	32	61.5	184
R.P.	24	61	160
P.P.	20	67	154
D.S.	—	—	—
J.S.	20	71	158
T.S.	25	75	195
J.T.	34	66.5	165
B.W.	38	69	165
D.W.	33	83	195
D.Z.	21	72	198
Others			
J.F.	42	68	150
G.H.	—	—	—
J.L.	—	—	—
S.L.	—	—	—
W.R.	51	65	145

Note: All subjects are male.

B. Scheme of experiments

I. *Subject D.B.*
Phase shifts
Effects of heat
Pitch-forward axis
Yaw axis
Random axis

II. *Subject G.C.*
Phase shifts
Performance
Pitch-forward axis
Roll-left axis
Pitch and roll axis

III. *Subject N.C.*
Occlusion
Phase shifts
Performance
Extended rotation
Pitch-forward axis
Pitch-backward axis
Roll axis
Yaw axis
Pitch and roll axis
Pitch, roll, and yaw axis
Random axis

IV. *Subject E.D.*
Phase shifts
Effects of heat
Performance
Pitch-forward axis
Roll-left axis
Yaw axis
Pitch and roll axis
Pitch, roll, and yaw axis
Random axis

V. *Subject M.D.*
Demonstration
Pitch axis

VI. *Subject D.E.*
Occlusion
Phase shifts
Effects of heat
Effects of cold
Pitch-forward axis
Yaw axis
Random axis

VII. *Subject S.H.*
Phase shifts
Performance
Pitch-forward axis

VIII. *Subject F.H.*
Phase shifts
Performance
Extended rotation
Pitch-forward axis
Roll-left axis
Yaw axis
Pitch and roll axis
Pitch and yaw axis
Roll and yaw axis
Pitch, roll, and yaw axis
Random axis

IX. *Subject R.K.*
Effects of heat
Extended rotation
Deconditioning and water immersion
Pitch axis
Yaw axis
Random axis

X. *Subject S.K.*
Performance
Deconditioning and water immersion
Pitch axis
Roll axis
Yaw-left axis
Pitch and roll axis
Pitch and yaw axis
Roll and yaw axis
Pitch, roll, and yaw axis
Random axis

XI. *Subject V.K.*
Effects of cold
Pitch-forward axis

XII. *Subject E.M.*
Impedance
Pitch axis
Roll-right axis
Yaw-left axis

XIII. *Subject L.M.*
Occlusion
Pitch-forward axis
Deconditioning and water immersion

XIV. *Subject J.N.*
Phase shifts

XV. *Subject E.O.*
Performance
Pitch and roll axis
Random axis

XVI. *Subject R.P.*
Extended rotation
Deconditioning and water immersion
Pitch axis

XVII. *Subject P.P.*
Effects of heat
Pitch-forward axis
Yaw axis
Random axis

B. Scheme of experiments (contd.)

XVIII. *Subject D.S.*
- Performance
- Pitch-forward axis
- Roll-left axis
- Yaw axis
- Yaw-right axis
- Pitch and roll axis
- Pitch and yaw axis
- Roll and yaw axis
- Pitch, roll, and yaw axis
- Random axis

XIX. *Subject J.S.*
- Phase shifts
- Performance
- Demonstration
- Cuff experiment
- Pitch-forward axis
- Roll-left axis
- Yaw axis
- Pitch and roll axis
- Pitch and yaw axis
- Roll and yaw axis
- Pitch, roll, and yaw axis
- Random axis

XX. *Subject T.S.*
- Occlusion
- Phase shifts
- Effects of cold
- Pitch-forward axis
- Pitch-backward axis

XXI. *Subject J.T.*
- Extended rotation
- Pitch

XXII. *Subject B.W.*
- Pitch axis
- Yaw axis
- Pitch and roll axis

XXIII. *Subject D.W.*
- Occlusion
- Effects of heat
- Effects of cold
- Deconditioning and water immersion
- Pitch axis
- Pitch-forward axis
- Pitch-backward axis
- Yaw axis
- Random axis

XXIV. *Subject D.Z.*
- Effects of heat
- Effects of cold
- Performance
- Pitch-forward axis
- Roll axis
- Yaw axis
- Pitch and roll axis
- Pitch and yaw axis
- Roll and yaw axis
- Pitch, roll, and yaw axis
- Random axis

Additional subjects

XXV. *Subject J.F.*
- Phase shifts
- Performance
- Pitch-forward axis
- Spit
- Turntable
- Pitch and roll axis
- Pitch and yaw axis
- Yaw and roll axis

XXVI. *Subject G.H.*
- Demonstration
- Pitch-forward axis
- Pitch-backward axis
- Roll-left axis
- Roll-right axis
- Yaw-left axis
- Yaw and roll axis
- Random axis

XXVII. *Subject J.L.*
- Demonstration
- Pitch axis
- Roll-left axis

XXVIII. *Subject S.L.*
- Demonstration
- Pitch axis

XXIX. *Subject W.R.*
- Phase shifts

C. *Test run schedule*

Date	Subject	Scheduled profile	Run time	Medical monitor	Comments
		Pure pitch, 3 rpm	6'11"		
		Roll and yaw, 3 rpm	3'58"		
		Roll, pitch, yaw, 3 rpm	4'05"		
		Pitch and roll	3'34"		
		Pure roll, 3 rpm	3'30"		
		Pitch and yaw, 3 rpm	3'16"		
		Random, 3 rpm	1'08"		
7 Mar. 1968	E.O.	Pitch and roll, 3, 6, 12 rpm	8'30"	Dr. Meyer	Same; slight nausea control capabilities.
		Random	1'15"		
		Random	2'35"		
20 Mar. 1968	F.H.	Yaw, 3 rpm	3'02"		Control capability in 8 modes.
		Pitch, 3 rpm	3'32"		
		Pitch and yaw, 3 rpm	3'07"		
		Roll and yaw, 3 rpm	3'27"		
		Pitch and roll, 3 rpm	3'37"		
		Roll, pitch, yaw, 3 rpm	3'38"		
		Roll, 3 rpm	1'07"		Subject rest during breaks in roll test.
		Roll, 3 rpm	1'28"		
		Roll, 3 rpm	1'17"		
		Random	2'17"		
20 Mar. 1968	J.F.	Spit, 3, 6, 12, 24, 30 rpm	12'13"	Dr. Meyer	
21 Mar. 1968	J.S.	Yaw, 3 rpm	3'02"	Dr. Brown	Control capability in 8 modes.

C. Test run schedule (contd.)

Date	Subject	Scheduled profile	Run time	Medical monitor	Comments
		Roll and yaw, 3 rpm	3'46"		
		Roll, pitch, yaw, 3 rpm	3'00"		
		Roll	3'40"		
		Pitch	2'50"		
		Pitch and yaw	1'30"		
		Pitch and yaw	2'28"		Rest (1 min. 5 sec.) between two pitch and yaw runs.
		Pitch and roll	4'00"		
		Random	3'00"		
21 Mar. 1968	S.K.	Yaw, 3 rpm	6'17"	Dr. Brown	Control capability in 8 modes.
		Pitch, 3 rpm	2'24"		
		Pitch and yaw, 3 rpm	2'10"		
		Roll and yaw, 3 rpm	3'06"		
		Pitch and roll, 3 rpm	2'55"		
		Roll, pitch, yaw, 3 rpm	2'55"		
		Roll, 3 rpm	2'27"		
		Random, 3 rpm	3'20"		
			Extended rotation		
2 Apr. 1968	N.C.	Pitch forward, 6 rpm	59'50"	Dr. Meyer	Includes respiratory maneuvers.
15 Apr. 1968	R.K.	Pitch forward, 6 rpm	54'30"		Nausea.
15 Apr. 1968	R.P.	Pitch forward, 6 rpm	22'27"		Includes respiratory maneuvers; nausea.
16 Apr. 1968	F.H.	Pitch forward, 6 rpm	58'49"		

C. *Test run schedule (contd.)*

Date	Subject	Scheduled profile	Run time	Medical monitor	Comments
		Deconditioning and water immersion			
3 Apr. 1968	S.K.	Pitch forward, 6 rpm	3'10"	Dr. Meyer	Control: pre-immersion.
3 Apr. 1968	S.K.	Pitch forward, 6 rpm	3'15"	Dr. Meyer	After 4 hours' immersion
	S.K.	Pitch forward, 6 rpm	3'23"		After 6 hours' immersion.
3 Apr. 1968	D.W.	Pitch forward, 6 rpm	3'04"	Dr. Meyer	Control: pre-immersion.
		Pitch forward, 6 rpm	3'24"		After 1 hour's immersion
		Pitch forward, 6 rpm	3'20"		After 6 hours' immersion.
3 Apr. 1968	L.M.	Pitch forward, 6 rpm	3'15"	Dr. Meyer	Control: pre-immersion.
		Pitch forward, 6 rpm	3'02"		After 2 hours' immersion.
4 Apr. 1968	R.K.	Pitch forward, 6 rpm	2'43"	Dr. Brown	Control: pre-immersion.
		Pitch forward, 6 rpm	3'17"		After 6 hours' immersion.
4 Apr. 1968	R.P.	Pitch forward, 6 rpm	3'16"	Dr. Brown	Control: pre-immersion.
		Pitch forward, 6 rpm	3'27"		After 6 hours' immersion.
		Instrument checkout, demonstration, and other runs			
7 Mar. 1968	J.S.	Pitch forward, 3-6 rpm			Telemetry checkout.
10 Nov. 1967	J.S.	Pitch forward, 6 rpm	6'03"		Thigh occlusion checkout.
		Pitch forward, 6 rpm	57"		
13 Nov. 1967	J.S.	Pitch forward, 6 rpm	3'07"		Thigh occlusion checkout; trial experiment.
			4'02"		
			4'32"		

C. *Test run schedule (contd.)*

Date	Subject	Scheduled profile	Run time	Medical monitor	Comments
3 Jan. 1968	J.F.	Pitch forward, 7-12 rpm			
12 Jan. 1968	L.M.	Aborted run			Terminated by medical monitor; infection.
7 Mar. 1968	G.H.	Yaw left	0'50"	Dr. Meyer	Demonstration of vehicle potential for sensitivity measurements.
		Yaw right	0'35"		
		Roll left	1'37"		
		Roll right	1'23"		
		Pitch forward	1'40"		
		Pitch backward	1'30"		
		Random	5'00"		
26 Mar. 1968	J.S.				Aborted hot run: instrument checkout.
31 Mar. 1967	S.L.	6 rpm	3'00"		Marked alteration bradycardia-tachycardia.
		12 rpm	3'00"		
19 Mar. 1968	W.R.	Pure yaw	3'10"	Dr. Brown	
		Pure roll	0'50"		
		Pitch	5'30"		
2 Apr. 1968	E.O.	Pitch forward, 29-30 rpm	2'29"		High rpm demonstration to SAM visitors.
17 Apr. 1968	M.D.	Pitch forward, 6 rpm	5'16"		Extended run terminated by subject; respiratory maneuvers.
			6'10"		
			4'00"		
			6'13"		
17 Apr. 1968	J.T.	Pitch forward, 6 rpm	5'15"		Aborted extended run; nausea.
			5'27"		

D. Test runs and duration for individual subjects

Subject	Test runs	Total time
D.B.	9	41'29"
G.C.	3	15'31"
N.C.	22	174'04"
E.D.	17	9'03"
M.D.	4	21'39"
D.E.	12	34'27"
F.H.	18	102'01"
S.H.	5	20'19"
R.K.	9	80'21"
S.K.	14	59'37"
V.K.	2	9'02"
E.M.	7	18'02"
L.M.	5	24'27"
J.N.	5	14'45"
E.O.	13	118'32"
P.P.	5	14'19"
R.P.	3	29'10"
D.S.	11	55'50"
J.S.	27	75'58"
T.S.	14	30'07"
J.T.	2	10'42"
B.W.	4	12'53"
D.W.	19	66'13"
D.Z.	14	46'54"
J.F.	16	68'47"
G.H.	7	10'35"
J.L.	8	5'46"
S.L.	2	6'00"
W.R.	3	9'30"
	280	1,186'03"

E. Phase II subject register

Phase II-A subjects

D.E.	MSgt. H. D. Engel
F.H.	TSgt. F. R. Hannon
S.H.	TSgt. S. E. Howard
J.N.	TSgt. J. C. Nichols
J.S.	A/1C J. M. Sigler
T.S.	Sgt. W. T. Springfield, Jr.
	Extra subject: Dr. Sam Lim

Phase II-B subjects

D.B.	Sgt. D. Brown
W.B.	Maj. W. Brown
G.C.	Capt. G. H. Cohen
N.C.	Capt. N. Creekmore, Jr.
E.D.	MSgt. E. Dinger
M.D.	SSgt. M. Dilks
D.E.	MSgt. H. D. Engel
F.H.	TSgt. F. R. Hannon
S.H.	TSgt. S. E. Howard
R.K.	SSgt. R. Korzendorfer
S.K.	SSgt. S. Konoval
V.K.	MSgt. V. E. Kirkland
E.M.	TSgt. E. Matney
L.M.	A/1C L. Miller
E.O.	TSgt. E. R. Osbon
R.P.	A/1C R. Perrili
P.P.	A/1C P. Paramore
D.S.	Sgt. D. Shaw
J.S.	A/1C J. M. Sigler
T.S.	Sgt. W. T. Springfield, Jr.
J.T.	TSgt. J. E. Todd
B.W.	MSgt. B. Wiggins, Jr.
D.W.	Sgt. D. Watson
D.Z.	A/1C D. Zawyrucha
	Extra subjects: Dr. J. Fletcher, Dr. Jose Li[illegible]na, W. E. Rothe, Col. George Halliwell

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13. ABSTRACT

Twelve tumbling problems, ranging from impaired performance to water immersion deconditioning, were investigated by using an important training and physiologic research tool--the All-Attitude Air-Bearing Research and Training Simulator (ARTS). The ARTS can move up to 60 rpm in roll, pitch, yaw, any combination of these, or random axis rotation.

In 280 test runs on a subject panel of 24 experienced and 5 inexperienced men, it was shown that among healthy persons there is a wide spectrum in their tolerance to tumbling. Evidence was obtained that men may be disoriented by tumbling, yet show no symptoms of motion sickness, and vice versa. In tests of numeric processing capability, random rotation, reliance on auditory input, and slow tumbling at 3 to 6 rpm (or above 30 rpm) gave the most difficulty. Experiments with occlusion of the blood circulation by using thigh cuffs suggested the importance of volume redistribution in controlling heart rate. The characteristic pattern of rhythmic cardio-acceleration and cardio-deceleration due to slow tumbling was abolished in 1 subject at 30 rpm, pitch forward. Combined stresses of tumbling and cold are tolerated better than combined stresses of tumbling and heat.

Other investigations which are described include: complex patterns of rotation and tumbling, respiratory effects, phase shifts at different rpm's, subject capability to perform a simulated flying movement during turning, body position effects, and the ability of some subjects to withstand continuous tumbling for at least 1 hour.

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Cardiovascular physiology						
Acceleration, physiologic						
All-Attitude Air-Bearing Research and Training Simulator (ARTS)						
Tumbling in space						

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